TRANSACTIONS

OF THE

AMERICAN INSTITUTE

OF

ELECTRICAL ENGINEERS

JANUARY TO DECEMBER 1904

VOL. XXIII.

PUBLISHED BY
THE AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS,
95 LIBERTY STREET,
NEW YORK, N. Y., U. S. A.
1905.

Copyright 1904
by the
AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS

Press of McILROY & EMMET, 22 Thames Street, New York

OFFICERS AND BOARD OF DIRECTORS.

1903-1904.

PRESIDENT.

BION J. ARNOLD.
Term expires 1904.

JUNIOR PAST-PRESIDENTS.

CHARLES P. STEINMETZ. CHARLES F. SCOTT.

VICE-PRESIDENTS.

Terms expire 1904.	Terms expire 1905.
C. O. MAILLOUX.	W. S. BARSTOW.
SCHUYLER S. WHEELER.	RALPH D. MERSHON.
JOHN W. LIEB, JR.	CALVIN W. RICE.

MANAGERS.

Terms expire 1904.	Terms expire 1905.	Terms expire 1906.
JOHN J. CARTY.	CHARLES A. TERRY.	SAMUEL SHELDON.
R. T. E. LOZIER.	TOWNSEND WOLCOTT.	GEORGE F. SEVER.
W. E. GOLDSBOROUGH.	GANO S. DUNN.	A. H. ARMSTRONG.
SAMUEL REBER.	E. H. MULLIN.	W. C. L. EGLIN.

TREASURER.

Terms expire 1904.

GEORGE A. HAMILTON,
463 West Street, New York.

SECRETARY.

RALPH W. POPE,
95 Liberty Street, New York.

PAST-PRESIDENTS.

NORVIN GREEN, 1884-5-6.	FRANK J. SPRAGUE, 1892-3.
FRANKLIN L. POPE, 1886-7.	EDWIN J. HOUSTON, 1893-4-5.
T. COMMERFORD MARTIN, 1887-8.	LOUIS DUNCAN, 1895-6-7.
EDWARD WESTON, 1888-9.	FRANCIS B. CROCKER, 1897-8.
ELIHU THOMSON, 1889-90.	A. E. KENNELLY, 1898-1900.
W. A. ANTHONY, 1890-91.	CARL HERING, 1900-1901.
ALEX. GRAHAM BELL, 1891-2.	CHARLES P. STEINMETZ, 1901-2.

CHARLES F. SCOTT, 1902-3.

STANDING COMMITTEES.

Executive Committee.

BION J. ARNOLD, Chairman.
J. J. CARTY.
GANO S. DUNN.
GEO. A. HAMILTON.
JOHN W. LIEB, Jr.
RALPH W. POPE.
CHARLES A. TERRY.

Library Committee.

WM. D. WEAVER, Chairman.
GANO S. DUNN.
WILLIAM J. JENKS.
CHARLES E. KNOX.
LEONARD WALDO.

Board of Examiners.

WM. MAVER, Jr., Chairman.
F. W. ROLLER.
HENRY A. LARDNER.
CECIL P. POOLE.
TOWNSEND WOLCOTT.

Editing Committee.

CARY T. HUTCHINSON, Chairman.
GEORGE F. SEVER.
HENRY A. LARDNER.

Committee on Papers.

S. SHELDON, Chairman.
A. H. ARMSTRONG.
A. J. BOWIE, Jr.
P. JUNKERSFELD.
JOHN P. KELLY.

Committee on Finance.

JOHN J. CARTY, Chairman.
W. S. BARSTOW.
E. H. MULLIN.

SPECIAL COMMITTEES.

Transmission Committee.

RALPH D. MERSHON, Chairman.
P. O. BLACKWELL.
C. C. CHESNEY.
A. M. HUNT.
P. M. LINCOLN.

Affiliated Societies.

OBERLIN SMITH, Chairman.
W. E. GOLDSBOROUGH.
J. W. LIEB, Jr.
R. T. E. LOZIER.
R. B. OWENS.

Committee on National Electric Code.

A. E. KENNELLY, Chairman.
L. A. FERGUSON.
P. G. GOSSLER.
F. A. C. PERRINE.
H. A. SINCLAIR.
ARTHUR WILLIAMS.
C. J. H. WOODBURY.

Committee on By-Laws.

RALPH W. POPE, Chairman.
CARY T. HUTCHINSON.
E. H. MULLIN.
W. D. WEAVER.
SAMUEL SHELDON.
WM. MAVER, Jr.

Comm. on Cadmium Cell.

H. S. CARHART, Chairman.
G. A. HAMILTON.
E. B. ROSA.
C. H. SHARP.
B. J. ARNOLD, Ex-Officio.

Committee on Telegraphy and Telephony.

A. E. KENNELLY, Chairman.
B. GHERARDI.
J. C. KELSEY.
K. B. MILLER.
H. L. REBER.

Standardization Committee.

H. J. RYAN, Chairman.
B. A. BEHREND.
LOUIS BELL.
CARL HERING.
J. S. PECK.
E. B. ROSA.
C. P. STEINMETZ.

Building Fund Committee.

CALVIN W. RICE, Chairman.
T. C. MARTIN.
J. G. WHITE.

Committee on Engineering Data.

H. W. BUCK, Chairman.
H. A. FOSTER.
W. I. SLICHTER.
E. A. MERRILL.

Reception Committee.

CALVIN W. RICE, Chairman.
ARTHUR WILLIAMS.
T. C. MARTIN.
CHAS. W. PRICE.
E. H. MULLIN.
CALVERT TOWNLEY.
F. C. BATES.
B. GHERARDI.
W. J. HAMMER

Conference Library Committee.

W. D. WEAVER, Chairman,
M. I. PUPIN,
FRANCIS W. JONES.

Local Organization Comm.

CHARLES F. SCOTT, Chairman
CALVIN W. RICE.
D. C. JACKSON.
W. C. L. EGLIN.
G. O. SQUIER.

Committee on Increase of Membership.

W. S. BARSTOW, Chairman
J. P. GILCHRIST.
W. E. GOLDSBOROUGH.
SAMUEL REBER.
GEO. D. SHEPARDSON.

Advisory Committee on Building Fund.

U. N. BETHELL, Chairman.
N. F. BRADY.
EUGENE GRIFFIN.
J. H. McGRAW.
C. W. PRICE.
SAMUEL REBER.
F. J. SPRAGUE.
ELIHU THOMSON.
SAMUEL INSULL.

Representatives on Board of Award, John Fritz Medal.

CARL HERING.
CHARLES P. STEINMETZ
CHARLES F. SCOTT.
BION J. ARNOLD.

Representatives on Joint Committee Union Engineering Building.

CHARLES F. SCOTT.
BION J. ARNOLD.
SCHUYLER S. WHEELER

CONTENTS.

Frontispiece—Portrait of Bion J. Arnold, President of the INSTITUTE.

ALTERNATING-CURRENT RAILWAY MOTORS.

MEETING AT NEW YORK, JANUARY 29, 1904.

Speed-Torque Characteristics of the Single-Phase Repulsion Motor.—By Walter I. Slichter (*Illustrated*) 1

The Alternating-Current Railway Motor.—By Charles P. Steinmetz (*Illustrated*) 9

Discussion on Alternating-Current Railway Motors by B. G. Lamme, A. S. McAllister, Bion J. Arnold, C. P. Steinmetz P. M. Lincoln, Walter I. Slichter, Ralph D. Mershon, A. H. Armstrong, Robert Lundell, O. S. Lyford, Jr., H. A. Wagner, Chas. F. Scott, B. A. Behrend, W. S. Franklin, Comfort A. Adams, Dugald C. Jackson 26

Discussion, at Pittsburg, February 2, 1904, on Alternating-Current Railway Motors by V. Karapetoff 78

MEETING AT CINCINNATI, FEBRUARY 15, 1904.

Single-Phase Railways.—By W. A. Blanck. (*Illustrated.*) 83

HIGH PRESSURE LINES.

MEETING AT NEW YORK, FEBRUARY 26, 1904.

The Conductivity of the Atmosphere at High Voltages.—By Harris J. Ryan. (*Illustrated.*) 101

Discussion by C. F. Scott, Samuel Sheldon, Harold B. Smith, P. H. Thomas, Harris J. Ryan, P. M. Lincoln, G. T. Hanchett, Elihu Thomson, Ralph D. Mershon, S. M. Kintner 135

Discussion at Pittsburg, March 10, 1904, by H. W. Fisher .. 145

European Practice in the Construction and Operation of High Pressure Transmission Lines and Insulators.—By Guido Semenza. (*Illustrated.*) 147

Discussion by J. W. Lieb, Jr., W. N. Smith, Bion J. Arnold, L. L. Perry, W. S. Dix, C. F. Scott 164

Discussion at Pittsburg, March 10, 1904, by N. J. Neall 166

Discussion at Chicago, April 26, 1904, on High Voltage Lines by W. A. Blanck, C. E. Freeman 168

HIGH PRESSURE TRANSMISSION.

MEETING AT NEW YORK, MARCH 25, 1904.

The Relative Fire-Risk of Oil Transformers and Air-Blast Transformers.—By E. W. Rice, Jr. 171

Discussion by F. A. C. Perrine, J. S. Peck, Calvert Townley, Ralph D. Mershon, C. E. Skinner, H. G. Stott, P. N. Nunn, P. M. Lincoln, C. L. de Muralt, O. S. Lyford, Jr., Howard Bayne, W. L. Waters, Irving A. Taylor, Norman T. Wilcox, A. C. Pratt, H. A. Lardner, H. F. Parshall, R. S. Kelsch, H. W. Tobey, Wm. J. Hazard, E. P. Roberts, W. S. Moody 175

The Use of Group-Switches in Large Power-Plants.—By L. B. Stillwell. ... 199
Discussion by Alex Dow, Ralph D. Mershon, H. G. Stott, L. B. Stillwell, Wm. B. Jackson, Irving A. Taylor, Gilbert Wright, John B. Taylor, H. F. Parshall. ... 204
Oil-Switches for High Pressures.—By E. M. Hewlett. ... 215
Discussion by C. C. Chesney, F. A. C. Perrine, Alex Dow, Ralph D. Mershon, C. F. Scott, P. N. Nunn, C. L. de Muralt, H. F. Parshall. ... 217
Terminals and Bushings for High-Pressure Transformers.—By Walter S. Moody. ... 225
Discussion by Ralph D. Mershon, C. E. Skinner, Irving A. Taylor, N. M. Snyder, A. C. Pratt. ... 231
Discussion at Chicago, March 29, 1904, on High-Pressure Transmission by James Lyman, W. A. Blanck, P. Junkersfeld, G. N. Eastman, D. W. Roper, G. H. Lukes, W. G. Carlton, E. O. Sessions, I. E. Brooke, Mr. Thomas, R. F. Schuchardt, Ed. Schildhauer. ... 236
Discussion at Pittsburg, April 7, 1904, on High-Pressure Transmission by J. W. Farley, N. J. Neall, A. B. Bond, B. P. Rowe. ... 246
Discussion at Philadelphia, May 9, 1904, on High-Pressure Transmission by H. F. Sanville, W. C. L. Eglin. ... 249

ALTERNATING-CURRENT GENERATORS.

MEETING AT NEW YORK, APRIL 22, 1904.

The Mechanical Construction of Revolving-Field Alternators.—By David B. Rushmore. (*Illustrated.*) ... 253
A Contribution to the Theory of the Regulation of Alternators.—By H. M. Hobart and F. Punga. (*Illustrated.*) ... 291
Discussion by C. A. Adams, Jr., B. A. Behrend, W. L. Waters, Gano S. Dunn, David B. Rushmore, F. A. C. Perrine, Bradley T. McCormick ... 323
Discussion at Pittsburg, May 5, 1904, by V. Karapetoff ... 337
Discussion by H. M. Hobart and Franklin Punga (by letter) 340

MEETING AT SEATTLE, WASH., APRIL 14, 1904.

Operation of Synchronous Converters.—By S. C. Lindsay ... 345

ANNUAL MEETING.

AT NEW YORK, MAY 17–18, 1904.

Notes on Fly-Wheels.—By H. H. Barnes, Jr. (*Illustrated.*) ... 353
Predetermination of Sparking in Direct-Current Machines.—By W. L. Waters. (*Illustrated.*) ... 365
Effect of Self Induction on Railway Motor Commutation.—By E. H. Anderson. (*Illustrated.*) ... 379
On the Calculation of Line Batteries.—By W. E. Winship. (*Illustrated.*) ... 393
Wave Form Variations of a Long-Distance Line.—By George H. Rowe. (*Illustrated.*) ... 403
Data and Tests on a 10 000 Cycle-per-Second Alternator.—By B. G. Lamme. (*Illustrated.*) ... 417
The Single-Phase Induction Motor.—By William S. Franklin. (*Illustrated.*) ... 429
Discussion on papers presented at the Annual Meeting, by W. L. Waters, E. R. Douglas, R. B. Treat, E. H. Anderson, W. S. Franklin, Clarence P. Feldman, Bion J. Arnold, H. Ward Leonard, Thorbur Reid, F. J. White, Lamar Lyndon, W. E. Winship, F. D. Newbury, F. B. Crocker, H. H. Barnes, Jr., H. Y. Hall, Jr., A. S. McAllister ... 443

HIGH-TENSION TRANSMISSION.

MEETING AT CHICAGO, JUNE 21–22, 1904.

Protection of Cables from Arcs Due to the Failure of Adjacent Cables.—By W. G. Carlton 471
Discussion by Ralph D. Mershon, W. F. Wells, H. C. Wirt, W. G. Carlton, H. B. Alverson, E. M. Lake, A. M. Hunt, J. W. F. Blizard 475

Synchronous Motors for Regulation of Power-Factor and Line Pressure.—By B. G. Lamme 481
Discussion by F. O. Blackwell, W. L. Waters, H. B. Gear, W. B. Jackson, F. A. C. Perrine, Ralph D. Mershon, S. B. Storer, Chas. F. Scott, J. S. Peck, H. W. Buck, T. J. Johnston 494

Long Spans for Transmission Lines.—By F. O. Blackwell. (*Illustrated.*) 511
Discussion by Ralph D. Mershon, F. O. Blackwell, A. S. Hatch, Chas. F. Scott, N. J. Neall, Wm. Hoopes, Eugene Clark, Bion J. Arnold, W. D. Ball, F. A. C. Perrine, W. B. Jackson, H. B. Alverson, Peter Junkersfeld, H. C. Wirt, S. B. Storer, R. F. Hayward 514

Conditions for Continuous Service over Lines Operated in Parallel.—By M. H. Gerry, Jr. (*Illustrated.*) 547
Discussion by Ralph D. Mershon, P. H. Thomas 551

The Use of Ground Shields in Transformers.—By J. S. Peck 553
Discussion by Ralph D. Mershon, H. C. Wirt, C. E. Skinner, P. H. Thomas, W. L. Waters 555

The Protection of High-Pressure Transmission Lines from Static Discharges.—By H. C. Wirt. (*Illustrated.*) 557
Discussion by J. S. Peck, Ralph D. Mershon, N. J. Neall, F. O. Blackwell, H. C. Wirt, R. F. Hayward, P. H. Thomas, N. M. Snyder, John Pearson 561

Answers to Questions Relative to High-Tension Transmission. (A Report of the High-Tension Transmission Committee.) 571
Discussion by J. H. Finney, Ralph D. Mershon, Peter Junkersfeld, Bion J. Arnold, L. Schuler, S. B. Storer, F. A. C. Perrine, Eugene Clark, W. B. Jackson, N. J. Neall, James Lyman 605
General discussion on High-Tension Transmission by W. G. Carlton, Bion J. Arnold, Chas. F. Scott, Peter Junkersfeld, Ralph D. Mershon, N. J. Neall, G. N. Eastman, H. B. Alverson, F. Woodmansee, G. R. Radley 609

ANNUAL CONVENTION.

ST. LOUIS, SEPT. 14, 1904.

President's Address.—By Bion J. Arnold 615
Discussion on Different Methods and Systems of Using Alternating Current in Electric Railway Motors by Chas. P. Steinmetz, R. Kaye Gray, Professor Perry, B. G. Lamme, C. V. Drysdale, Bion J. Arnold, F. J. Sprague, Elihu Thomson 624

TRANSMISSION OF INTELLIGENCE.

MEETING AT NEW YORK, OCTOBER 28, 1904.

The Telautograph.—By James Dixon. (*Illustrated.*) 645

The Transposition of Electrical Conductors.—By Frank F. Fowle. (*Illustrated.*) 659

HEAVY ELECTRIC TRACTION.

MEETING AT NEW YORK, NOVEMBER 25, 1904.

Problems in Heavy Electric Traction.—By O. S. Lyford, Jr., and W. N. Smith. (*Illustrated.*) 691

Discussion by L. B. Stillwell, C. O. Mailloux, H. Ward Leonard, W. S. Franklin, A. H. Armstrong, C. T. Hutchinson, W. N. Smith, E. E. Ries, O. S. Lyford, Jr., Wm. McClellan.... 723
Discussion at Pittsburg, December 5, 1904, by N. W. Storer. 752

TRANSMISSION PROBLEMS.

MEETING AT NEW YORK, DECEMBER 23, 1904.

The Maximum Distance to which Power can be Economically Transmitted.—By Ralph D. Mershon. (*Illustrated.*)..... 759
Discussion by John W. Lieb. Jr., H. G. Stott, Philip Torchio, P. G. Gossler, J. E. Wallace, M. H. Gerry, Jr., A. E. Kennelly, Chas. F. Scott, C. L. de Muralt, Ralph D. Mershon..... 782
Discussion at Pittsburg, January 9, 1905, by S. M. Kintner, P. M. Lincoln, H. W. Fisher, N. J. Neall..... 801
Discussion at Philadelphia, January 9, 1905, by Wm. McClellan, A. B. Stitzer, Carl Hering, H. A. Foster..... 805

APPENDIX.

Report of the Board of Directors for the Fiscal Year Ending April 30, 1904..... 807
Report of Committee on Local Organizations..... 815
Report of Committee on the Cadmium Cell..... 827
Report of Library Committee..... 833

INDEX.

BUSINESS OF THE INSTITUTE.

Address, President Bion J. Arnold, at St. Louis, Mo., September 14, 1904 615
Annual Convention, St. Louis, Mo., September 14, 1904 615
Arnold, Bion J., President of the INSTITUTE 1903–4, Portrait of, Frontispiece
Balance Sheet, Secretary's 812
Board of Directors, Report of 807
Cadmium Cell, Report of Committee on the 827
Chicago Branch, Meeting, April 26, 1904 168
Chicago Branch, Meeting, March 29, 1904 236
Chicago Branch, Meeting, June 21–22, 1904 471
Cincinnati Branch, Meeting, February 15, 1904 83
Committee on High-Tension Transmission, Report of 571
Convention, Annual, St. Louis, Mo., September 14, 1904 615
Deaths During the Year 812
Directors, Report of Board of 807
Disbursements and Receipts 812
General Meeting, Twenty-first, St. Louis, Mo., September 14, 1904 615
High-Tension Transmission Committee, Report of 571
INSTITUTE Receipts and Disbursements 812
Library Committee, Report of 833
Local Organizations, Report of Committee on 815
Meeting, Chicago Branch, April 26, 1904 168
Meeting, Chicago Branch, March 29, 1904 236
Meeting, Chicago Branch, June 21–22, 1904 471
Meeting, Cincinnati Branch, February 15, 1904 83
Meeting, New York, January 29, 1904 1
Meeting, New York, February 26, 1904 101
Meeting, New York, March 25, 1904 171
Meeting, New York, April 22, 1904 253
Meeting, New York, May 17–18, 1904 353
Meeting, New York, October 28, 1904 645
Meeting, New York, November 25, 1904 691
Meeting, New York, December 23, 1904 759
Meeting, Philadelphia Branch, May 9, 1904 249
Meeting, Philadelphia Branch, January 9, 1905 805
Meeting, Pittsburg Branch, February 2, 1904 78
Meeting, Pittsburg Branch, March 10, 1904 ..... 145, 166
Meeting, Pittsburg Branch, April 7, 1904 246
Meeting, Pittsburg Branch, May 5, 1904 337
Meeting, Pittsburg Branch, December 5, 1904 752
Meeting, Pittsburg Branch, January 9, 1905 801
Meeting, Seattle Branch, April 14, 1904 345
Membership, Resumé of 811
New York Meeting, January 29, 1904 1
New York Meeting, February 26, 1904 101

New York Meeting, March 25, 1904..... 171
New York Meeting, April 22, 1904..... 253
New York Meeting, May 17–18, 1904..... 353
New York Meeting, October 28, 1904..... 645
New York Meeting, November 25, 1904..... 691
New York Meeting, December 23, 1904..... 759
Philadelphia Branch Meeting, May 9, 1904..... 249
Philadelphia Branch Meeting, January 9, 1905..... 805
Pittsburg Branch Meeting, February 2, 1904..... 78
Pittsburg Branch Meeting, March 10, 1904.....145, 166
Pittsburg Branch Meeting, April 7, 1904..... 246
Pittsburg Branch Meeting, May 5, 1904..... 337
Pittsburg Branch, Meeting December 5, 1904..... 752
Pittsburg Branch Meeting, January 9, 1905..... 801
Portrait of Bion J. Arnold, President of the INSTITUTE 1903–4, Frontispiece
President Bion J. Arnold's Address, at St. Louis, Mo., September 14, 1904..... 615
Receipts and Disbursements..... 812
Report, Annual, of Board of Directors..... 807
Report, Annual, of Committee on Local Organizations..... 815
Report of High-Tension Transmission Committee..... 571
Report of Library Committee..... 833
Report of Committee on the Cadmium Cell..... 827
Seattle Branch Meeting, April 14, 1904.....345
Secretary's Balance Sheet..... 812
Twenty-first General Meeting, St. Louis, Mo., September 14, 1904.. 615
Treasurer's Report..... 814

PAPERS AND DISCUSSIONS.

Alternating Current Generators 253
Alternating-Current Railway Motor, The. (Illustrated.) (*Charles P. Steinmetz.*) 9
Alternator, Data and Tests on a 10 000 Cycle per Second. (Illustrated.) 417
Alternators, Contribution to the Theory of the Regulation of. (Illustrated.) 291
Alternators, Revolving Field, Mechanical Construction of. (Illustrated.) 253
Atmosphere, Conductivity of, at High Voltages. (Illustrated.) ... 101
Batteries Line, On the Calculations of. (Illustrated.) 393
Bushings and Terminals for High-Pressure Transformers 225
Calculation of Line Batteries. (Illustrated.) (*W. E. Winship.*) .. 393
Conditions for Continuous Service over Lines Operated in Parallel. (Illustrated.) (*M. H. Gerry, Jr.*) 547
Conductivity of the Atmosphere at High Voltages. (Illustrated.) (*Harris J. Ryan.*) 101
Conductors, Electrical, Transposition of. (Illustrated.) 659
Construction and Operation of High-Pressure Transmission Lines and Insulators, European Practice in the. (Illustrated.) 147
Contribution to the Theory of the Regulation of Alternators. Illustrated.) (*H. M. Hobart and F. Punga.*) 291
Converters, Synchronous, Operation of 345
Data and Tests on a 10 000 Cycle-per-Second Alternator. (Illustrated.) (*B. G. Lamme.*) 417
Different Methods and Systems of Using Alternating Current in Electric Railway Motors. Discussion at St. Louis, Mo., Sept. 14, 1904 624
Discussion on Alternating-Current Generators, at New York, April 22, 1904 ..... 323, 340
Discussion on Alternating-Current Generators, at Pittsburg, May 5, 1904 337
Discussion on Alternating-Current Railway Motors, at New York, January 29, 1904 26
Discussion on Alternating Current Railway Motors, at Pittsburg, February 2, 1904 78
Discussion on Different Methods and Systems of Using Alternating Current in Electric Railway Motors, at St. Louis, Mo., Sept. 14, 1904 624
Discussion on Heavy Electric Traction, at New York, November 25, 1904 723
Discussion on Heavy Electric Traction, at Pittsburg, Pa., December 5, 1904 752
Discussion on High-Pressure Lines at Chicago, April 26, 1904 168
Discussion on High-Pressure Lines at New York, February 26, 1904. 164
Discussion on High-Pressure Lines at Pittsburg, March 10,1904 .. 166
Dscussion on High-Pressure Transmission, at Chicago, March 29, 1904 236
Discussion on High-Pressure Transmission, at New York, March 25, 1904 ..... 175, 204, 217, 231
Discussion on High-Pressure Transmission, at Philadelphia, May 9, 1904 249
Discussion on High-Pressure Transmission, at Pittsburg, April 7, 1904 246

Discussion on High-Tension Transmission, at Chicago, June 21–22, 1904. . . . . 475, 494, 514, 551, 555, 561, 605, 609
Discussion on Papers Presented at the Annual Meeting, New York, May 17–18, 1904. 443
Discussion on The Conductivity of the Atmosphere at High-Voltages, at New York, February 26, 1904. 135
Discussion on The Conductivity of the Atmosphere at High-Voltages, at Pittsburg, March 10, 1904. 145
Discussion on Transmission Problems, at New York, December 23, 1904. 782
Discussion on Transmission Problems, at Philadelphia, Pa., January 9, 1905. 805
Discussion on Transmission Problems, at Pittsburg, Pa., January 9, 1905. 801
Distance, Maximum, to which Power Can be Economically Transmitted. (Illustrated.) 759
Effect of Self-Induction on Railway Motor Commutation. (Illustrated.) (*E. H Anderson.*) 379
Electric Traction, Problems of Heavy. (Illustrated.) 691
European Practice in the Construction and Operation of High-Pressure Transmission Lines and Insulators. (Illustrated.) (*Guido Semenza.*) 147
Fire Risk of Oil and Air-Blast Transformers, The Relative. 171
Fly-Wheels, Notes on. (Illustrated.) 353
Generators, Alternating-Current. 253
Ground Shields in Transformers, The Use of. 553
Group-Switches, The Use of, in Large Power Plants. 199
Heavy Electric Traction. 691
High-Pressure Lines. 101
High-Pressure Transmission. 171
High-Pressure Transmission Lines and Insulators, European Practice in the Construction and Operation of. (Illustrated.) 147
High Tension Transmission. 471
High Voltages, Conductivity of the Atmosphere at. (Illustrated.). 101
Induction Motor, Single-Phase. (Illustrated.) 429
Intelligence, Transmission of. 645
Line Batteries, On the Calculation of. (Illustrated.) 393
Line, Long Distance, Wave Form Variations of a. (Illustrated.). . 403
Long Spans for Transmission Lines. (Illustrated.) (*F. O. Blackwell.*) 511
Maximum Distance to which Power Can be Economically Transmitted. (Illustrated.) (*Ralph D. Mershon.*) 759
Mechanical Construction of Revolving-Field Alternators. (Illustrated.) (*David B. Rushmore.*) 253
Motor, Single-Phase Induction. (Illustrated.) 429
Motors, Electric Railway, Different Methods and Systems of Using Alternating Current in, Discussion at St. Louis, Mo., Sept. 14, 1904. 624
Motors, Railway, Alternating-Current. 1
Motors, Synchronous, for Regulation of Power Factor and Line Pressure. 481
Notes on Fly-Wheels. (Illustrated.) (*H. H. Barnes, Jr.*) 353
Oil-Switches for High Pressures. (*E. M. Hewlett.*) 215
Operation of Synchronous Converters. (*S. C. Lindsay.*) 345
Parallel, Lines Operated in, Conditions for Continuous Service. (Illustrated.) 547
Power Factor and Line Pressure, Synchronous Motors for Regulation of. 481
Predetermination of Sparking in Direct-Current Machines. (Illustrated.) (*W. L. Waters.*) 365
Problems of Heavy Electric Traction. (Illustrated.) (*O. S. Lyford, Jr., and W. N. Smith.*) 691
Problems, Transmission. 759

Protection of Cables from Arcs Due to the Failure of Adjacent Cables. (*W. G. Carlton.*) ... 471
Protection of High-Pressure Transmission Lines from Static Discharges. (Illustrated.) (*H. C. Wirt.*) ... 557
Railway Motor, Alternating-Current. (Illustrated.) ... 9
Railway Motor Commutation, Effect of Self-Induction on. (Illustrated.) ... 379
Railways, Single-Phase. (Illustrated.) ... 83
Regulation of Power Factor and Line Pressure, Synchronous Motors for ... 481
Relative Fire-Risk of Oil and Air-Blast Transformers. (*E. W. Rice, Jr.*) ... 171
Report of Committee on High-Tension Transmission ... 571
Repulsion Motor, Single-Phase, Speed-Torque characteristics of the. (Illustrated.) ... 1
Revolving-Field Alternators, Mechanical Construction of. (Illustrated.) ... 253
Self-Induction, Effect of, on Railway Motor Commutation. (Illustrated.) ... 379
Service, Conditions for Continuous, over Lines Operated in Parallel. (Illustrated.) ... 547
Single-Phase Induction Motor. (Illustrated.) (*Wm. S. Franklin.*) ... 429
Single-Phase Railways. (Illustrated.) (*W. A. Blanck.*) ... 83
Single-Phase Repulsion Motor, Speed-Torque Characteristics of the. (Illustrated.) ... 1
Sparking in Direct Current Machines, Predetermination of. Illustrated.) ... 365
Speed-Torque Characteristics of the Single-Phase Repulsion Motor, (Illustrated.) (*Walter I. Slichter.*) ... 1
Static Discharges, The Protection of High-Pressure Transmission Lines from. (Illustrated.) ... 557
Switches, Oil-, for High Pressures ... 215
Switches, The Use of Group-, in Large Power Plants ... 199
Synchronous Converters, Operations of ... 245
Synchronous Motors for Regulation of Power Factor and Line Pressures. (*B. G. Lamme.*) ... 481
Telautograph, The. (Illustrated.) (*James Dixon.*) ... 645
Terminals and Bushings for High-Pressure Transformers. (*Walter S. Moody.*) ... 225
Tests, Data and, on a 10 000 Cycle-per-Second Alternator. (Illustrated.) ... 417
Theory of the Regulation of Alternators, Contribution to the. (Illustrated.) ... 291
Traction, Heavy Electric ... 691
Traction Problems of Heavy Electric. (Illustrated.) ... 691
Transformers, High Pressure, Terminals and Bushings for ... 225
Transformers, The Relative Fire-Risk of Oil and Air-Blast ... 171
Transformers, The Use of Ground Shields in ... 553
Transmission, High-Pressure ... 171
Transmission, High Tension ... 471
Transmission, High-Tension, Answer to Questions Relative to. (Report of Committee on High-Tension Transmission.) ... 571
Transmission Lines, High-Pressure, The Protection of from Static Discharges. (Illustrated.) ... 557
Transmission Lines, Long Spans for. (Illustrated.) ... 511
Transmission of Intelligence ... 645
Transmission Problems ... 759
Transposition of Electrical Conductors. (Illustrated.) (*Frank F. Fowle.*) ... 659
Use of Ground-Shields in Transformers. (*J. S. Peck.*) ... 553
Use of Group Switches in Large Power Plants. (*L. B. Stillwell.*) ... 199
Variations, Wave Form, of a Long Distance Line. (Illustrated.) ... 403
Wave Form Variations of a Long Distance Line. (Illustrated.) (*Geo. H. Rowe.*) ... 403

INDEX OF AUTHORS.

Adams, Comfort A., Jr., Discussion 63, 323, 328
Alverson, H. B., Discussion 477, 539, 612, 613
Anderson, E. H., Paper; 379 Discussion 453
Armstrong, A. H., Discussion 43, 741
Arnold, Bion J., President's Address 615; Discussion 40, 44, 45, 164, 459, 466, 469, 531, 540, 541, 605, 607, 609, 610, 642, 644
Ball, W. D., Discussion 532
Barnes, H. H., Jr., Paper 353; Discussion 461, 463, 464, 465, 466
Bayne, Howard, Discussion 188
Behrend, B. A., Discussion 49, 325 328
Blackwell, F. O., Paper 511; Discussion 494, 500, 524, 526, 530, 541, 563
Blanck, W. A., Paper 83; Discussion 168, 237, 241 242
Blizard, J. W. F., Discussion 479
Bond, A. B., Discussion 247
Brooke, I. E., Discussion 243
Buck, H. W., Discussion 506
Carlton, W. G., Paper 471; Discussion 238, 241, 242, 243, 244, 476, 477, 609, 610, 611, 613
Chesney, C. C., Discussion 217
Clark, Eugene, Discussion 530, 532, 536, 607
Crocker, F. B., Discussion 461
Dix, W. S., Discussion 164
Dixon, James, Paper 645
Douglass, E. R., Discussion 443
Dow, Alex, Discussion 204, 222
Drysdale, C. V., Discussion 640
Dunn, Gano S., Discussion 328
Eastman, G. N., Discussion 237, 241, 243, 245, 611, 612, 614
Eglin, W. C. L., Discussion 250
Farley, J. W., Discussion 246
Feldman, Clarence P., Discussion 455, 464, 465, 466
Finney, J. H., Discussion 605
Fisher, H. W., Discussion 145, 740 802
Franklin, W. S., Paper 429; Discussion 55, 454, 463, 464, 465, 466
Freeman, C. E., Discussion 168
Foster, H. A., Discussion 806
Fowle, Frank F., Paper 659
Gear, H. B., Discussion 496
Gerry, M. H., Jr., Paper 547; Discussion 791
Gossler, P. G., Discussion 789
Gray, R. Kaye, Discussion 632
Hall, H. V., Jr., Discussion 466
Hanchett, G. T., Discussion 141
Hatch, A. S., Discussion 524, 545
Hazard, Wm. J., Discussion 196
Hering, Carl, Discussion 806
Hewlett, E. M., Paper 215
Hayward, R. F., Discussion 543, 563
Hobart, H. M., Paper 291; Discussion 340
Hoopes, Wm., Discussion 527
Hunt, A. M., Discussion 477
Hutchinson, Cary T., Discussion 744

Jackson, D. C., Discussion 77
Jackson, W. B., Discussion 206, 497, 537, 607
Johnston, T. J., Discussion 509
Junkersfeld, P., Discussion 237, 239, 242, 243, 244, 245, 539, 605, 609, 614
Karapetoff, V., Discussion 78, 337
Kelsch, R. S., Discussion 193
Kennelly, A. E., Discussion 792
Kintner, S. M., Discussion 144, 801
Lake, E. M., Discussion 477
Lamme, B. G., Papers 417, 481; Discussion 26, 45, 46, 62, 633
Lardner, H. A., Discussion 192
Leonard, H. Ward, Discussion 456, 738
Lieb, J. W., Jr., Discussion 164, 165, 782
Lincoln, P. M., Discussion 42, 140, 185, 801
Lindsay, S. C., Paper 345; Discussion .....
Lukes, G. H., Discussion 238
Lundell, Robt., Discussion 45
Lyford, O. S., Jr., Paper 691; Discussion 45, 187, 750
Lyman, Jas., Discussion 236, 242, 608
Lyndon, Lamar, Discussion 458
McAllister, A. S., Discussion 468
McClellan, Wm., Discussion 750, 805
McCormick, Brady T., Discussion 330
Mailloux, C. O., Discussion 729
Mershon, Ralph D., Paper 759; Discussion 43, 143, 182, 204, 222, 231, 475, 500, 523, 532, 536, 537, 551, 555, 561, 605, 610, 611, 612, 613, 794, 795, 798
Moody, Walter S., Paper 225; Discussion 197
Muralt, C. L. de, Discussion 186, 223
Neall, N. J., Discussion 166, 246, 526, 533, 541, 542, 562, 608, 610 804
Newbury, F. D., Discussion 459
Nunn, P. N., Discussion 185, 223
Parshall, H. F., Discussion 193, 214, 224
Pearson, John, Discussion 568
Peck, J. S., Paper 553; Discussion 177, 505, 561
Perrine, F. A. C., Discussion 175, 221, 330, 498, 505, 534, 536, 540, 606
Perry, L. L., Discussion 164
Perry, Professor, Discussion 632
Pratt, A. C., Discussion 191, 234
Punga, F., Paper 291; Discussion 340
Radley, G. R., Discussion 614
Reid, Thorburn, Discussion 450, 451
Rice, E. W., Jr., Paper 171
Ries, E. E., Discussion 749
Roberts, E. P., Discussion 196
Roper, D. W., Discussion 237
Row, Geo. H., Paper 403
Rowe, B. P., Discussion 247
Rushmore, David B., Paper 253; Discussion 329, 330
Ryan, Harris J., Paper 101; Discussion 138, 139, 140
Sanville, H. F., Discussion 249
Schildhauer, Edw., Discussion 244
Schuler, L., Discussion 605
Schuchardt, R. F., Discussion 244
Scott, C. F., Discussion 48, 135, 165, 222, 501, 505, 525, 533, 609, 610, 613, 793
Semenza, Guido, Paper 147
Sessions, E. O., Discussion 243, 244
Sheldon, Samuel, Discussion 136
Skinner, C. E., Discussion 183, 231, 555, 802
Slichter, Walter I., Paper 1; Discussion 42, 45

Smith, Harold B., Discussion 137
Smith, W. Nelson, Paper 691; Discussion 164, 746
Snyder, N. M., Discussion 234, 567
Sprague, F. J., Discussion 642
Steinmetz, C. P., Paper 9; Discussion 41, 45, 46, 624
Stillwell, L. B., Paper 199; Discussion 205, 723
Stitzer, A. B., Discussion 805
Storer, N. W., Discussion 752
Storer, S. B., Discussion 501, 506, 542, 606, 607
Stott, H. G., Discussion 184, 205, 782
Taylor, Irving A., Discussion 190, 209, 232
Taylor, Jno. B., Discussion 211
Thomas, P. H., Discussion 138, 139, 140, 243, 551, 555, 565
Thomson, Elihu, Discussion 142, 643
Tobey, H. W., Discussion 195
Townley, Calvert, Discussion 181
Torchio, Philip, Discussion 784, 789
Treat, R. B., Discussion 449
Wagner, H. A., Discussion 45
Wallace, J. E., Discussion 789
Waters, W. L., Paper 365; Discussion 189, 326, 443, 449, 495, 556
Wells, W. F., Discussion 475
White, F. J., Discussion 457
Wilcox, Norman T., Discussion 191
Winship, W. E., Paper 393; Discussion 458
Wirt, H. C., Paper 557; Discussion 475, 541, 542, 555, 563
Woodmansee, F., Discussion 612, 613, 614
Wright, Gilbert, Discussion 210

A paper presented at the 183d meeting of the American Institute of Electrical Engineers, New York, January 29, 1904.
Copyright 1904, by A. I E. E.

SPEED-TORQUE CHARACTERISTICS OF THE SINGLE PHASE REPULSION MOTOR.

BY WALTER I. SLICHTER.

The single-phase commutator motor has attracted considerable attention of late, as there is quite a demand in railway work as well as in numerous other lines for an alternating-current motor that will start under a heavy load with a reasonable consumption of energy. At present it appears that a commutator motor is the only type that will fulfil these conditions.

For some months past the writer of this paper has been in charge of a series of experiments with various types of alternating-current commutator motors. During these experiments much attention was given to the repulsion motor. It is the purpose of this paper to place before the INSTITUTE some of the results obtained, and to point out some of the characteristics of the motor which give promise of making it a very prominent factor in some lines of electric railroading of the future.

For the benefit of those not already familiar with this type of motor, it may be here stated that it is a single-phase commutating motor, resembling very much a regular direct-current armature in an induction-motor field. The resemblance to the induction motor is carried still further in that there is no electrical connection between the primary and secondary. This makes it possible to wind the primary for a high line voltage, while the voltage of the secondary winding is chosen at such a value as may be commutated satisfactorily, since it is short circuited on itself through its brushes.

The motor has the same characteristics as the direct-current series motor; namely, maximum torque at starting, increasing torque with increasing current and decreasing speed, and comparatively constant efficiency through a wide range of speed.

The maximum speed of the motor is limited only by the load and impressed voltage and has no relation to the synchronous speed.

Due to the reactance of the motor circuits, the power-factor at starting is low and will be with any alternating-current motor; but in the repulsion motor a low power-factor does not mean small torque. On the contrary, the maximum torque occurs simultaneously with the lowest power-factor; that is, at starting. The power-factor of the repulsion motor rises very rapidly with the speed; it reaches a good value at one-third synchronous speed, and values near to 90% are obtained over a considerable range of speed. For this reason a large number of poles is not necessary and frequencies of 25, 40, and even 60 cycles may be employed.

The rotating conductors of the secondary cutting the primary flux generate a leading e.m.f., which causes a leading current to flow therein and gives the high power-factor of the motor. In the plain repulsion motor, this leading current never reaches a value great enough to compensate entirely for the magnetizing and other wattless currents at available speeds, but the phenomenon is utilized to obtain unity power-factor in the compensated type by the addition of a second circuit. The inherently good power-factor of the repulsion motor makes it possible to use larger clearance between field and armature than is permitted in induction motors, thus greatly increasing its value in railway work where comparatively large air-gaps are necessary.

The curves given are partly from test and partly from calculation of motors having air-gaps of 0.125 inch on a side, and more. The air-gap of corresponding stationary induction motors would be 0.040 inch and more.

The efficiency, while not so good as in a direct-current motor, is yet very good, reaching values of from 80 to 85, including gear-loss for sizes ranging from 50 to 200 horse-power.

Commutation at normal speeds is inherently good, due to the revolving field. As the speed decreases, the current increases rapidly, producing a tendency to spark, but with the reduced voltage of starting the rush of current is limited to values within the range of good commutation, as in the direct-current motor.

At higher speeds, ranging above one-and-a-half times synchronism, the frequency of commutation becomes high and sparking appears.

The motor of Fig. 1 will start with 75% of full

voltage and twice full-load current with no trouble from sparking. As these curves are prepared upon a railway-motor basis, and full-load current will produce a rise of 75° C. after one hour's run, the ability of the repulsion motor successfully to commutate overloads is equal to that of the direct-current series motor; in fact, better, due to the short-circuited commutator which makes flashing-over impossible.

Fig. 1 shows the characteristics of a repulsion motor plotted with revolutions per minute as a base. These curves are taken from tests on a 60-horse power, 25-cycle, 500-volt motor; they show the rapidly rising efficiency and power-factor

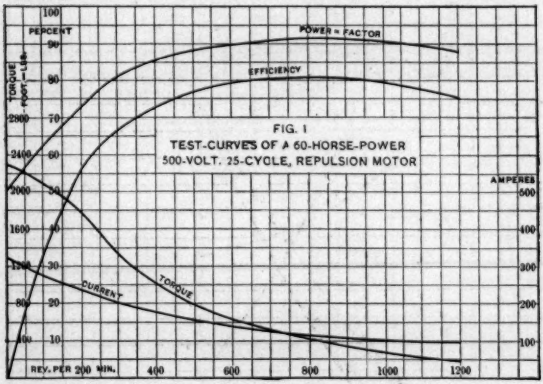


FIG. 1
TEST-CURVES OF A 60-HORSE-POWER 500-VOLT, 25-CYCLE, REPULSION MOTOR

and the large torque at starting. The starting torque is 2300 ft. lbs., with an input of 325 amperes, and the normal torque during acceleration, 450 ft. lbs. at 750 revolutions and 125 amperes. Thus the starting torque is five times normal and the starting current 2.6 times normal; or the torque per ampere at starting is 1.92 times what it is at normal speed, should occasion demand the full starting capacity of the motor.

This gives an idea of the steep speed-characteristics of the motor, which are even better shown in Fig. 2. The full lines refer to a later type of repulsion motor and the broken lines to a standard direct-current series railway motor; these curves are plotted in the usual way with current as a base.

This shows that the torque increases more rapidly with increasing current in the repulsion motor than in the series; and conversely that the speed of the repulsion motor increases more rapidly with decreasing current than in the series motor. Efficiency, including gear-loss, is given and is 84.5% at the

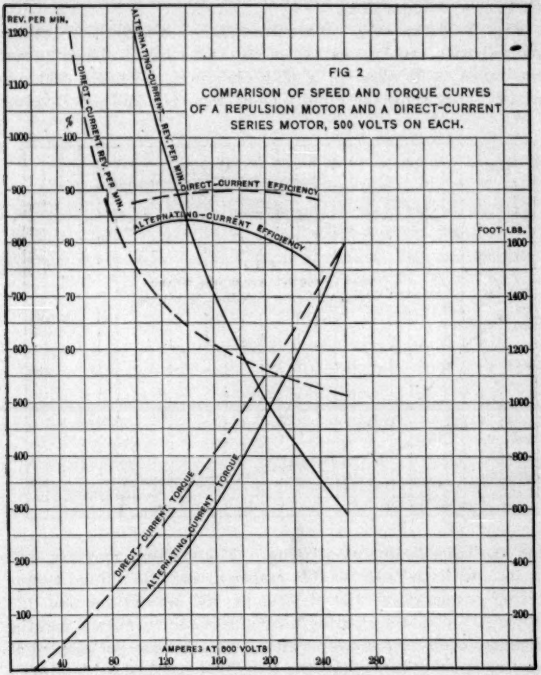


FIG 2

COMPARISON OF SPEED AND TORQUE CURVES OF A REPULSION MOTOR AND A DIRECT-CURRENT SERIES MOTOR, 500 VOLTS ON EACH.

maximum for the alternating-current motor. This motor was designed with the steep speed-characteristics for acceleration work, while the motor of Fig. 4 is designed for constant-speed running and has not such steep curves but better constants at light loads.

The characteristics show the repulsion motor to be admirably adapted for acceleration work, the efficiency of acceleration being higher than in direct-current work, due to the possibility of obtaining fractional e.m.f.s with alternating currents without introducing the dead resistance losses of the direct-current system of control.

This is shown in the curves on Fig. 3, which gives the acceleration curves from test of a 25-ton car equipped with two 60-h.p. repulsion motors. The full lines indicate the repulsion motor characteristics and the broken lines those calculated for a direct-current equipment. The gearing is chosen for the same

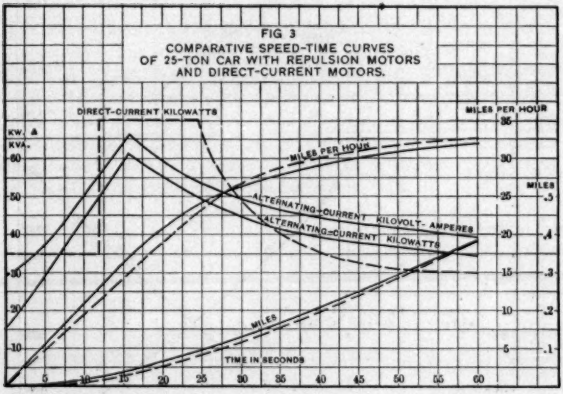


FIG. 3
COMPARATIVE SPEED-TIME CURVES OF 25-TON CAR WITH REPULSION MOTORS AND DIRECT-CURRENT MOTORS.

free-running speed, 33 miles per hour, the same average acceleration, and the same distance covered in sixty seconds. For the direct-current motor the curve of kilowatts input, miles per hour, and miles traveled, are given as calculated; and for the alternating-current motor the kilovolt-ampere input, kilowatt input, miles per hour, and miles traveled, from test.

The repulsion motor remains on the controller only 16 seconds and the direct-current motor 25 seconds. The maximum power taken by the direct-current motor is 70 kw. and by the repulsion motor 61 kw. or 67 kilovolt-amperes. At the end of 25 seconds, the total kw.-hour input in the two cases is 0.375 for the direct current and .30 for the alternating current. At the

end of 60 seconds both cars have covered a distance of 0.039 mile and have reached practically the same speed of 32.5 miles per hour, the kw.-hour input being 0.72 for the direct current and 0.685 for the alternating current.

By comparing the areas of the kilowatt curves in the two cases the gain or rather the saving by the use of the alternating current is readily seen. It is also worthy of note that the volt-ampere input of the alternating-current motor is least at starting; that is, the line current is least. As this is the time at which the power-factor is lowest, it is seen that the effect of the low power-factor on the regulation of the system is much modified by the small value of the current.

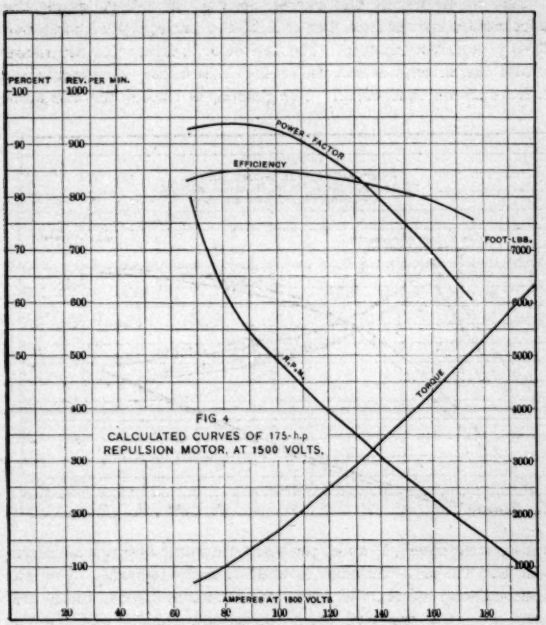


FIG 4
CALCULATED CURVES OF 175-h.p. REPULSION MOTOR, AT 1500 VOLTS.

Fig. 4 shows the calculated characteristics of a 175-h.p. rail-

way repulsion motor having an air-gap of 0.15 inch and wound for 1500 volts and 25 cycles. The efficiency, including gear-loss, is 85% at the maximum and the power-factor is 93. Such a motor is designed for heavy, slow-speed locomotive work, which is probably one of the most promising fields for the alternating-current motor. It is readily seen how well it is adapted for freight haulage by the fact that the efficiency of 85% is attained at a speed as low as 500 revolutions, thus permitting a speed of 12 to 15 miles per hour, with a good gear reduction.

Thus the repulsion motor is well adapted for acceleration work as well as for efficient running at light loads, and having good constants at low speeds is well adapted for freight haulage at low speeds.

The curves given in this paper all refer to the simple repulsion motor, the theory of which is given in the paper by Mr. C P. Steinmetz. There are many variations of the repulsion motor, more or less complicated, from which a better power-factor and even a better efficiency have been obtained in test. However, a description of these various schemes with their characteristics would require sufficient space to warrant a distinct paper and it is hoped to present such to the INSTITUTE at a future date.

BLANK
PAGE

A paper presented at the 183d meeting of the American Institute of Electrical Engineers, New York, January 29, 1904.
Copyright 1904, By A. I. E. E.

THE ALTERNATING-CURRENT RAILWAY MOTOR

BY CHARLES P. STEINMETZ.

For electric railroading a motor is required which maintains a high value of efficiency over a wide range of speed. That is, the torque per ampere input at constant impressed voltage must increase with decrease of speed, the speed increase with decrease of load.

In electric motors, torque is produced by the action of a magnetic field upon currents flowing in an armature movable with regard to the field. If then the field is constantly excited—shunt motor on constant potential—the torque is approximately proportional to the current, the speed approximately constant at all loads. If the field is excited by the main current of the motor—series motor on constant potential—the field strength and thereby the torque per ampere varies approximately proportional to the current, and thereby the load, the whole torque approximately proportional to the square of the current and the speed inversely proportional to the current, leaving saturation out of consideration. That is, the motor has the characteristic specified above for a railway motor.

Since the direction of rotation of the direct-current motor is independent of the direction of the impressed e.m.f., with laminated field the direct-current motor can be operated with alternating currents. By the use of alternating currents it becomes possible to transfer current from circuit to circuit by induction, and instead of passing the main-line current through the armature of the alternating-current motor, the armature circuit can be closed upon itself and the current induced therein as transformer secondary by a stationary primary coil in the main circuit surrounding the armature.

Condition of operation of the direct-current motor type on

alternating current is, however, that the current in field and armature reverses simultaneously. This is by necessity the case in the series motor. In the shunt motor, however, the armature current as energy current should be in phase with the impressed e.m.f., while the field current as magnetizing current lags nearly 90°. To bring it back into phase, W. Stanley tried condensers in series in the field circuit, but failed, due to the impossibility of neutralizing the self-induction of the field which varies with the commutation and the frequency, by the negative self-induction of the condensers, which varies with the frequency in the opposite direction. The solution of the problem has been found by the use of polyphase systems, by utilizing for the field excitation an e.m.f. in quadrature with the armature currents acted upon by the field magnetism. As I have shown elsewhere, the polyphase induction motor can be considered as a development of the direct-current shunt motor for alternating-current circuits, and indeed has all the shunt motor characteristics regarding speed, torque, etc. As railway motor the induction motor has therefore not been exploited, although it has been strongly recommended in those very few cases where it appeared good engineering. Experimental work with polyphase induction motor railways has been carried on continuously since 1893.

While in the early days of alternating-current motor development, all other engineers were industriously developing the constant-speed stationary motor type, with shunt motor characteristic, only Rudolph Eickemeyer of Yonkers was far-sighted enough to realize the vast future of alternating-current railroading, and to appreciate the absolute necessity of the series motor characteristic for railway work, and undertake the development of the single-phase alternating-current series motor. I had the good fortune at that time to be associated with Mr. Eickemeyer.

As was pointed out by G. Kapp, I believe in 1888, the power-factor of the alternating-current series motor is inherently low, since the same magnetic flux which induces, proportional to the frequency of rotation, the e.m.f. of useful work in the armature conductors, induces in the field coils an e.m.f. of self-induction, proportional to the frequency of alternation. Hence, giving the armature the same number of turns as the field (which is more than permissible in good practice, since good practice requires weak armature and strong field), even at synchronous speed the e.m.f. of rotation of the armature would still only be

equal to the e.m.f. of self-induction of the field; and the power-factor, allowing for an additional self-induction of the armature, would be below 70 per cent. This probably deterred the other engineers from considering the alternating-current series motor.

Eickemeyer solved the difficulty by designing the armature with a number of turns several times greater than the field (24 to 7 in the first motor built) and neutralizing the armature self-induction and reaction by a stationary secondary circuit surrounding the armature at right angles electrically to the field circuit (the "cross-coil," as he called it), and either short-circuited upon itself or energized by the main current in opposite direction to the current in the armature.

In January, 1891, I tested the first motor of this type, a bipolar motor with the following constants:

Field: Two coils of 14 turns No. 10 B & S wire, connected in parallel.

Armature: 24 coils of four turns each of No. 12 B & S wire.

Secondary circuit: Two coils of 18 turns each of No. 10 B & S wire connected in parallel.

At 100 cycles and 150 volts impressed e.m.f., this motor gave at three-fourths synchronous speed:

Current: 45 amperes.

I^2R: 400 watts.

Hysteresis and eddy currents: 900 watts.

Total output, including friction: 4000 watts.

Hence:

Efficiency, 75.5%

Power-factor, 79%

The starting current of this motor at 150 volts was 70 amperes.

As bipolar motor with the very high frequency then used, the speed, 4500 revolutions at three-fourths synchronism, was undesirably high, so we immediately proceeded to build an 8-pole motor In this, solid copper rings were used as secondary circuits surrounding the armature and neutralizing its self-induction, with an effective copper-section more than four times that of the armature conductors. The ratio of armature series turns to field series turns was about 4. This motor was tested in 1892. The record of tests is given in Fig. 1, the observed values being marked on the curves. For comparison on this sheet is also given the direct-current voltage required to operate this motor at the same speed and current.

As seen, when approaching synchronous speed, the power-

factor is nearly 90 per cent. The commutation was fair at 85 cycles, the highest frequency at which our factory engine was able to drive the alternator, and perfect at 33 cycles.

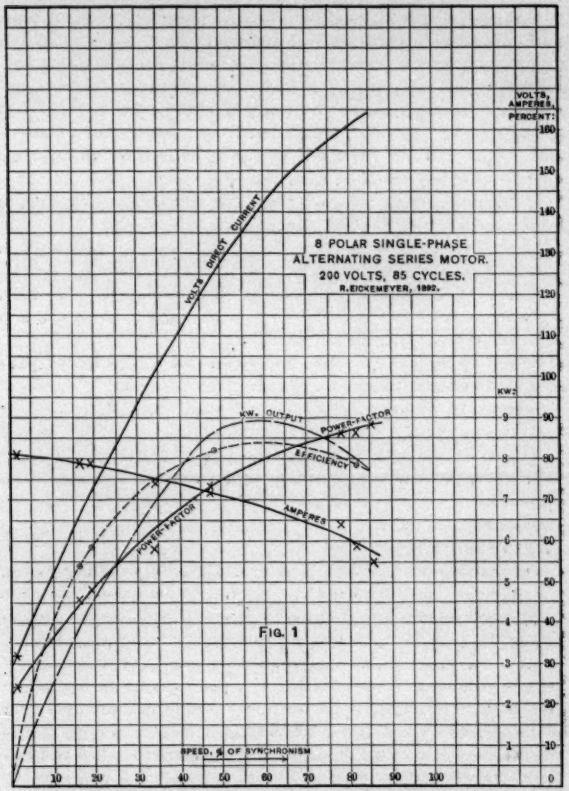


FIG. 1

A number of railway motors of this type were designed. The great difficulty, however, was that during these early days 125 to 133 cycles was the standard frequency in this country, 60 cycles hardly considered, and 25 cycles not yet proposed.

The efficiency of this alternating-current series motor is slightly lower than that of the same motor on direct-current circuit, due:

1. To the hysteresis loss in the field.

2. The hysteresis loss in the armature core, which is of full frequency up to synchronism and of still higher frequency, the frequency of rotation, beyond synchronism.

3. The I^2R loss in the short-circuited secondary conductors surrounding the armature.

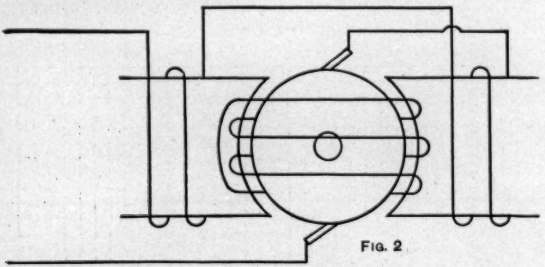


FIG. 2

As seen, to make the alternating-current series motor practicable, the transformer feature must be introduced, by having its armature as primary circuit closely surrounded by a short-circuited secondary circuit, as shown diagrammatically in Fig. 2.

Instead of closing the stationary circuit upon itself as secondary circuit and feeding the main current into the rotating armature as primary circuit, mechanically the same results would obviously be obtained by using the stationary circuit as primary energized by the main current, and closing the armature upon itself as secondary by short circuiting the brushes and thereby

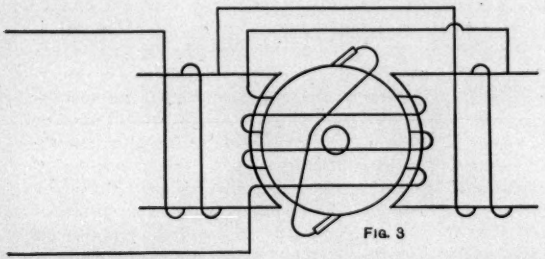


FIG. 3

keeping the main current and the line potential away from the armature, as shown diagrammatically in Fig. 3. This introduces the great advantage of reversing the sign of the uncompensated part of the armature self-induction, so that it is subtractive, which results in an essential improvement of the power-factor, especially at low speed.

This is shown in Fig. 4, where with the speed as abscissas, in per cent of synchronism, are plotted the power-factor of the Eickemeyer compensated series motor of Fig. 1, of ratio armature to field = 4, and the power-factor of one of the first railway repulsion motors, of ratio armature to field = 3.5.

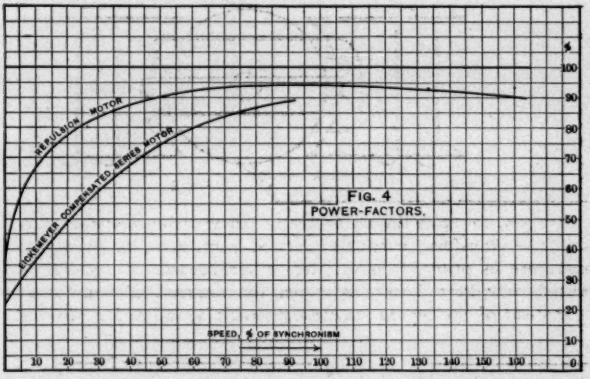


FIG. 4
POWER-FACTORS.

The compensation of the armature self-induction in Fig. 3 is based on the feature of the transformer that primary and secondary current are in opposition to each other. The secondary current of the transformer, however, lags slightly less than 180° behind the primary current; that is, considering it in the reverse direction, is a leading current with regard to the primary current. The current in the armature in Fig. 3 is, therefore, a leading current with respect to the line current, and so not only does not add an additional lag but reduces the lag caused by the self-induction of the field-exciting coil.

This motor then consists of a short-circuited armature surrounded by two coils at right angles with each other and connected in series, as illustrated in Fig. 5; the one, A_2, parallel

with the effective armature circuit, acting as primary of a transformer to induce the secondary armature current; the other, A_1, the field-exciting coil. The ratio of turns of these coils, n_2, to n_1, is the ratio of effective armature series turns to field turns, as discussed before. Obviously, these two coils can be replaced by one coil at an angle with the position of brushes as shown in Fig. 6, and the cotangent of the angle of the axis of this coil with the position of the brushes is above ratio; that is, the smaller this angle the greater is the ratio of armature to field turns; that is, the better the power-factor of the motor.

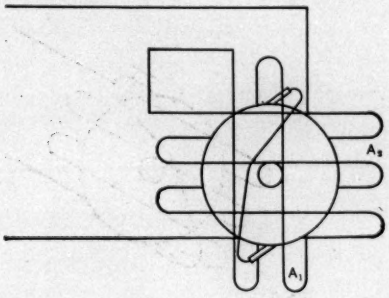
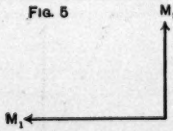


FIG. 5



This motor, Fig. 6, is Professor Elihu Thomson's repulsion motor.

In the armature an e.m.f. is induced by the alternation of the magnetic field, M_2, of coil A_2, proportional to M_2 and to the impressed frequency and in quadrature with M_2; and an e.m.f. is induced by the rotation through the magnetic flux M_1 of coil A_1, proportional to M_1 and to the frequency of rotation and in phase with M_1. These two e.m.fs. must be equal and opposite, since the armature is short circuited (neglecting the resistance and self-inductive reactance of the armature), and at synchronism, M_1 and M_2 are, therefore, equal and in quadrature with

each other; that is, in the armature of the motor, Fig. 5, and therefore of the repulsion motor, Fig. 6, at synchronism a uniform rotating field exists and the hysteresis loss in the armature core is therefore zero at synchronism and at other speeds proportional to the difference between speed and synchronism; that is, to the slip, just as in the polyphase induction motor; while in the motor, Fig. 2, the hysteresis loss in the armature core is proportional to the impressed frequency or the frequency of rotation, whichever is the higher frequency. The hysteresis loss of the repulsion motor is therefore lower than that of the same motor as compensated series motor.

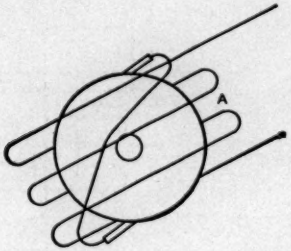
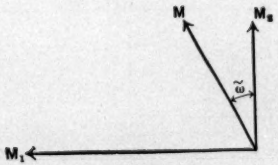


Fig. 6



In general, if in the repulsion motor in Fig. 6 the magnetic flux in line with the brushes, which does not induce e.m.f. by rotation but only by alternation, is denoted by M_2; the magnetic flux in quadrature with the brushes which induces e.m.f. in the armature by its rotation but not by the alternation of the flux, by M_1; and the magnetic flux in the axis of the primary coil A, which is much nearer to M_2 than to M_1, since good power-factor requires a small angle ω, by M, the two e.m.fs. induced in the armature, by the rotation through the flux M_1, are:

$$E_1 = 2\pi N_0 M_1 n,$$

By the alternation of the flux M_2.

$$E_2 = -j\,2\pi N M_2 n$$

Where n = number of armature turns,
N = impressed frequency;
N_0 = frequency of rotation.

Since, approximately, $E_2 = E_1$, it is,

$$j N_0 M_1 = N M_2$$

or

$$j M_1 : M_2 = N : N_0 \qquad (1)$$

That is: M_1 and M_2 are in quadrature in phase and the ratio of their intensity is inversely proportional to the ratio of speed to synchronism.

That is, in the repulsion motor an elliptically rotating field exists which becomes circular; in other words, a uniformly rotating field, at synchronism. Below synchronism the component M_1, which induces e.m.f. by the rotation of the armature is greater than M_2, the more the lower the speed. The flux M interlinked with the primary coil is, however, nearer to M_2 and therefore below synchronism, especially at low speeds, the magnetic flux which induces e.m.f. by the rotation of the armature and so represents the useful work, is greater than the magnetic flux which interlinks with the primary coil and so gives the lag of the primary current. This accounts for the high power-factor of the repulsion motor at low speeds.

Neglecting resistance and self-inductive reactance, it is,

$$M = \text{constant},$$

corresponding to the impressed voltage.

From equation (1) it follows:

$$M_2 = j M_1 (N_0/N)$$

Hence,

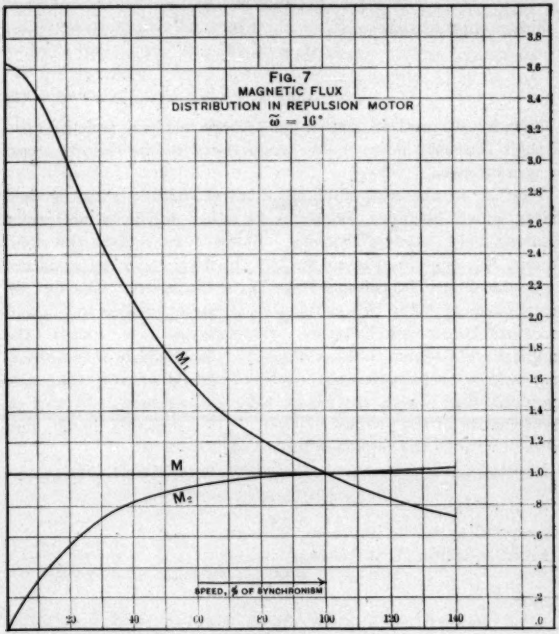
$$\begin{aligned} M &= M_2 \cos\omega + M_1 \sin\omega \\ &= M_1 [\sin\omega + j\,(N_0/N)\cos\omega] \end{aligned}$$

$$\left.\begin{aligned} M_1 &= \frac{M}{\sin\omega + j\,(N_0/N)\cos\omega} \\ M_2 &= \frac{M}{\cos\omega - j\,(N/N_0)\sin\omega} \end{aligned}\right| \qquad (2)$$

or, absolute:

$$M_1 = \frac{M}{\sqrt{\sin^2 \omega + (N_0/N)^2 \cos^2 \omega}}$$

$$M_2 = \frac{M}{\sqrt{\cos^2 \omega + (N/N_0)^2 \sin^2 \omega}} \qquad (7)$$



At synchronism: $N_0 = N$, it is:

$$M_1 = M_2 = M$$

At standstill: $N_0 = 0$, it is:

$$M_1 = \frac{M}{\sin \omega}$$

$$M_2 = 0$$

In Fig. 7 are shown the two quadrature components M_1 and M_2 of the magnetic field of the repulsion motor, for $\omega = 16°$ and $M = 1.0$.

In the theoretical investigation and practical calculation of the repulsion motor, just as in the polyphase and single-phase induction motor, the transformer feature is made the starting point and the motor considered as a transformer, the secondary of which is standing at a constant angle ω with regard to the primary, so that motion results from the repulsive thrust existing between primary and secondary.

Let in vector denotation:

E_0 = impressed e.m.f., used as zero vector e_0;

I = primary current;

I_1 = secondary current reduced to the primary by the ratio of turns (the same as customary in induction motors);

Z = primary exciting impedance that is, primary induced e.m.f., divided by primary current at open secondary circuit;

Z_0 = primary self-inductive impedance;

Z_1 = secondary self-inductive impedance reduced to the primary circuit;

ω = angle between primary and secondary axis; that is, angle of shift of brushes from the position of complete transformer action;

$a = (N_0/N)$ = ratio of speed to frequency.

The total m.m.f. acting upon the primary coil is then: Primary current I plus component of secondary current acting in the direction of the primary, or $I_1 \cos \omega$.

Hence,

$$I + I_1 \cos \omega$$

This, then, is the primary exciting current; and the primary induced e.m.f. is therefore $(I + I_1 \cos \omega) Z$.

The primary impedance voltage is $I Z_0$.

Hence,

$$e_0 = Z (I + I_1 \cos \omega) + I Z_0.$$

In the secondary circuit an e.m.f. is induced by its rotation through the magnetic flux M_1 in quadrature with the secondary axis, which is in phase with this magnetic flux. This magnetic flux M_1 is due to the component of primary current acting in this direction: $I \sin \omega$, since the secondary current exerts no m.m.f. at right angles to the axis of the secondary coil. The e.m.f. induced thereby is in phase with I.

This e.m.f., induced by flux M_1 is therefore,

$$E_1 = a \times I \sin \omega \qquad (4)$$

In the secondary, an e.m.f. is induced also by the alternation of the magnetic flux M_2 in the axis of the secondary coil.

This magnetic flux is produced by the m.m.f. of the secondary current I_1 and the component of primary current acting in this direction: $I \cos \omega$, hence, due to

$$I_1 + I \cos \omega$$

and the e.m.f. induced hereby is

$$E_2 = -Z (I_1 + I \cos \omega)$$

The impedance e.m.f. of the secondary circuit is $Z_1 I_1$, and since the secondary is short circuited, it is

$$Z (I_1 + I \cos \omega) + Z_1 I_1 - a x I \sin \omega = 0$$

These are the two fundamental equations of the repulsion motor:

Primary circuit:

$$e_0 = Z (I + I_1 \cos \omega) + I Z_0$$

Secondary circuit: (5)

$$0 = -a x I \sin \omega + Z (I_1 + I \cos \omega) + Z_1 I_1$$

Where we assumed the impressed e.m.f. e_0 as zero vector

From the second equation it follows:

$$I_1 = \frac{-I (Z \cos \omega - a x \sin \omega)}{Z + Z_1}$$

Substituting this in the first equation, gives:

Primary current;

$$I = \frac{e_0}{Z} \cdot \frac{Z + Z_1}{a x \sin \omega \cos \omega + Z \sin^2 \omega + Z_0 + Z_1 + \frac{Z_0 Z_1}{Z}} = e_0 (a_1 + j a_2) \tag{6}$$

Secondary current;

$$I_1 = \frac{e_0}{Z} \cdot \frac{Z \cos \omega - a x \sin \omega}{a x \sin \omega \cos \omega + Z \sin^2 \omega + Z_0 + Z_1 + \frac{Z_0 Z_1}{Z}} = e_0 (b_1 + j b_2)$$

Hence,

Power-factor: $\cos \phi = \dfrac{a_1}{\sqrt{a_1^2 + a_2^2}}$

Volt-ampere input; $Q_0 = e_0 I = e_0^2 \sqrt{a_1^2 + a_2^2}$

Power input; $P_0 = /e_0, I/' = e_0^2 a_1$

Power output; $P = /E_1 I_1/' = /a x I \sin \omega, I_1/'$

$$= a x \sin \omega / I, I_1 /'$$

$$= a x e_0^2 \sin \omega (a_1 b_1 + a_2 b_2)$$

Torque;
$$T = (P/a) = x \sin \omega / I, I_1/^1$$
$$= x e_0^2 \sin \omega (a_1 b_1 + a_2 b_2)$$

Efficiency;
$$\gamma = \frac{P}{P_0} = \frac{a x \sin \omega (a_1 b_1 + a_2 b_2)}{a_1}$$

etc.

Substituting

$Z_0 + Z_1 = Z^1 = r^1 - j x^1$ = total internal self-inductive impedance. Neglecting minor terms, it is, approximately:

Primary current;
$$I = \frac{e_0}{(a x \sin \omega \cos \omega + r^1) - j (x \sin^2 \omega + x^1)} \tag{7}$$

Secondary current;
$$I_1 = - \frac{e_0 (\cos \omega - j a \sin \omega)}{(a x \sin \omega \cos \omega + r^1) - j (x \sin^2 \omega \; x^1)} \tag{8}$$

Angle of lag;
$$\tan \phi = \frac{x \sin^2 \omega + x^1}{a x \sin \omega \cos \omega + r^1} \tag{9}$$

Torque;
$$T = \frac{e_0^2 x \sin \omega \cos \omega}{(a x \sin \omega \cos \omega + r^1)^2 + (x \sin^2 \omega + x^1)^2} \tag{10}$$

The secondary current leads the primary current by angle
$$\tan x_1 = a \tan \omega$$

The secondary current comes in phase with the primary impressed e.m.f. e_0,

if
$$\frac{a \sin \omega}{\cos \omega} = \frac{x \sin^2 \omega + x^1}{a x \sin \omega \cos \omega + r^1}$$

hence,
$$a = - \frac{r^1}{2 x \sin \omega \cos \omega} + \sqrt{\frac{x^1}{x \sin^2 \omega} + \frac{(r^1)^2}{4 x^2 \sin^2 \omega \cos^2 \omega}}$$

Above this speed, the secondary current leads the primary impressed e.m.f. e_0, hence magnetizes.

At $a = 1$, that is, at synchronism, the secondary current equals the primary current, $I_1 = I$, but leads by the angle of brush-shift ω.

At infinite speed, $a = \infty$.

$$I = 0$$

That is; the primary current decreases with increasing speed, down to zero at infinite speed. (In the ordinary induction motor the current can never fall below a certain minimum value, the exciting current).

In this case,

$$I_1 = j \frac{e_0}{x \cos \omega}$$

that is, lags 90° behind the primary impressed e.m.f., hence is 90° ahead of the phase of a transformer secondary current, and supplies the magnetizing current of the magnetic circuit, just as a condenser in the secondary circuit of a transformer would do.

At standstill:

$$a = 0;$$

$$I = \frac{e_0}{r^1 - j\,(x \sin^2 \omega + x^1)}$$

$$I_1 = \frac{e_0 \cos \omega}{r^1 - j\,(x \sin^2 \omega + x^1)}$$

$$\tan \phi = \frac{x \sin^2 \omega + x^1}{r^1}$$

$$T = \frac{e_0^2\, x \sin \omega \cos \omega}{(r^1)^2 + (x \sin^2 \omega + x^1)^1}$$

Current and torque are a maximum, the power-factor a minimum at standstill.

Backward rotation:

For negative values of speed a the torque T is still positive, hence opposed to the rotation, and the repulsion motor with reversed brush-angle ω acts as brake.

The primary current,

$$I = \frac{e_0}{(a\, x \sin \omega \cos \omega + r^1) - j\,(x \sin^2 \omega + x^1)}$$

for negative values of speed a becomes wattless, when

$$a\, x \sin \omega \cos \omega + r^1 = 0$$

or

$$a = -\frac{r^1}{x \sin \omega \cos \omega}$$

For higher negative values of a, or if at a speed greater than $a = (r^1/x \sin \omega \cos \omega)$ (a very low speed), the brush-angle ω is reversed, the energy component of the primary current becomes negative; that is, the motor returns power into the line.

Unlike the plain series motor, which never returns power into the line, the repulsion motor when reversed becomes a generator, consumes mechanical power as brake and returns electric power into the line, even at low speeds. Experiment verifies this feature.

Discussion of Theory.

In the preceding outline of the theory of the single-phase alternating-current repulsion motor, the impedances Z, Z_0, Z_1, have been assumed as constant.

While this is approximately the case in the ordinary induction motor, it is not the case with the repulsion motor which works over a wide range of magnetic flux densities.

With increasing load and thereby increasing current and decreasing speed, magnetic saturation is approached and causes a decrease of the impedances Z, Z_0, Z_1, which has to be taken into consideration in predetermining the characteristic curves of such a motor. Furthermore, the different component magnetic fluxes are affected differently by saturation. The flux M interlinked with the primary coil is approximately constant and therefore affected by saturation only indirectly, while the flux M_1 at right angles to the line of polarization of the secondary coil is approximately proportional to the load and so reaches saturation at high loads, and the impedances become thereby different in the different directions of the magnetic structure.

The m.m.fs. in the preceding have been treated as vector quantities, independent of their distribution around the periphery of the armature. This distribution, however, is different with the different m.m.fs. The m.m.f. causing the effective flux M_1 is due to a zone of the primary winding within the angle $\pm \omega$ from the axis of the secondary coil, hence nearly a concentrated winding, which gives a flat-topped flux distribution, while the flux M_2 in the direction of the axis of the secondary coil is that of a distributed winding or peaked. For the same m.m.f. the effective flux M_1 is therefore greater than the effective flux M_2. Taking this into consideration, gives the motor somewhat better characteristics than calculated above. Due to the different wave shapes of the fluxes M_1 and M_2, they are affected differently

by saturation. The flat-topped flux M_1 reaches saturation at a much higher value, but then over the whole range; while the peaked flux M_2 shows the effect of saturation at a lower value but then gradually, by a rounding off of the peak. In the repulsion motor it is therefore not sufficient merely to consider the resultant m.m.fs. as vectors but their distribution in the air-gap and the effect of saturation must be taken into consideration in the calculation and design of the motor. An exhaustive investigation hereof has been made by my assistant, Mr. M. Milch, and may be communicated at a later date.

The secondary circuit of the motor has been considered as the seat of two e.m.fs. induced respectively by the rotation through flux M_1 and by the alternation of flux M_2. These e.m.fs., however, have no separate existence. At synchronism, for instance, the magnetic field is an approximately uniformly rotating field and therefore no e.m.f. is induced in the armature conductors except that required to overcome the resistance. The secondary frequency varies with the load and thereby the secondary self-inductive reactance which we assumed as constant in the preceding discussion. This is best taken into consideration by a theory developed by my former assistant, Mr. S. Sugiyama, of Japan. The primary impressed alternating m.m.f. of the current I is resolved into two component m.m.fs. of half intensity, revolving synchronously in opposite directions. If now a = the ratio of speed to synchronism, the two oppositely revolving components of I revolve with regard to the secondary system with the speeds $(1-a)$ and $(1+a)$ respectively. The same consideration applies to the secondary m.m.f., I_1, and in the secondary system we then have induction at two frequencies, $1-a$ and $1+a$, of which the former becomes zero at synchronism. That is, at synchronism the secondary current in the armature conductors is of double frequency, similar as in the ordinary single-phase induction motor. At other speeds it is the superposition of two currents of the frequencies $1-a$ and $1+a$, respectively. This theory more closely allies the repulsion motor with the ordinary induction motor. Using the same values of secondary impedance, Z_1, for both components, obviously leads to identically the same equations as given in the preceding.

The complete investigation of the repulsion motor must also take into consideration the current flowing in the armature coil during the moment where the coil is short circuited by the

brushes passing from commutator segment to segment. The m.m.f. of this short-circuit current of commutation is at right angles to the axis of secondary polarization of current, I_1, hence has the angle of brush-shift $-(90-\omega)$. A corrective term must therefore be applied, taking this phenomenon into consideration, essentially of the character of a repulsion machine with negative or generator brush-angle of $(90-\omega)$ and very high effective secondary resistance. This term is very small or negligible at speeds up to a point somewhat beyond synchronism but becomes noticeable at speeds considerably above synchronism, due to the decrease of the main current at these speeds. The main effect of this phenomenon is that the power-factor of the motor instead of increasing indefinitely with the speed up to 100% at some very high speed (and then decreasing again slightly, with leading current), reaches a maximum somewhere between 90 and 97% according to the constants of the motor, and then very slightly decreases with increasing speed as shown in the curve of the power-factor of a repulsion motor in Fig. 2.

DISCUSSION OF STEINMETZ AND SLICHTER PAPERS.

B. G. LAMME:—In the paper presented before the AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS in September, 1902, the speaker called attention to the fact that there were but two types of single-phase alternating-current motors having suitable characteristics for railway service; viz., that called the "Series Type," and the "Repulsion Type." Both of these motors have armatures like direct-current motors, with commutators and brush holders. Attention was called to the fact that both motors have suitable characteristics for railway service, as both automatically give variable-speed characteristics with changes in load. That paper primarily described a single-phase railway system, and the motor formed but an element in the general system. It was a very general opinion at that time that the success of the commutator type of motor for large sizes was doubtful, and the sparking feature was considered a fundamental source of trouble. It was generally conceded that if a motor with series characteristics could be made to operate successfully, it would be a great step in advance in the railway field.

Since that time single-phase railway systems have been more fully developed. Practically no departures from the general system then indicated have been furnished, and the types of motors developed have been along the lines of the two motors indicated in that paper.

Up to the present time the only suitable motors suggested for this work have been of the commutator type, and have been those having series characteristics. The speaker has suggested that all these motors can be considered broadly under the one class of series motors, as they all have the series characteristics of the direct-current series motor. The speaker further suggested that they be subdivided into the "Straight-Series" type and the "Transformer-Series" type. The transformer-series could also be arranged in two classes; viz., one in which the armature or field is supplied by an external transformer, and one in which the transformer is placed in the motor itself; this latter is the repulsion type of motor.

Figs. 1, 2, and 3 illustrate the three classes. Fig. 1 being the straight-series, Fig. 2 the transformer-series, and Fig. 3 the repulsion motor. Fig. 2 would be considered as a true series motor, although the armature and field are not directly in series, yet most of the characteristics described as belonging in the repulsion motor apply directly to the transformer motor shown in the figure. Comparing the relations of these motors; viz., the straight-series and the repulsion motor, we will first take up the straight-series.

In this motor, if properly designed, two pressures can be considered; viz., that across the field circuit, and that across the armature circuit. The armature pressure can be made practically non-inductive so that the input of the armature will represent practically true energy. The pressure across the field

is practically at right angles to the armature pressure, and represents very closely the wattless component supplied by the motor. The resultant of these two pressures will then be the line pressure. The power-factor of the motor when running is represented practically by the pressure across the armature winding, increased slightly by the losses in the field-core and winding. Therefore, for high power-factors it is important that the pressure across the armature circuit be made as high as possible, relatively to the applied pressure, and that across the field as low as possible.

There are three ways in which to increase the pressure across the armature; viz., by increase in speed, by increase in the number of wires in series on the armature, and by increase in flux through the armature.

By increase in speed and increase of the wires in series, the armature pressure will be increased without affecting the field

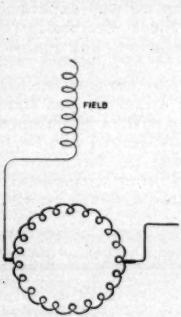


FIG. 1

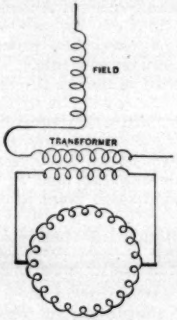


FIG. 2

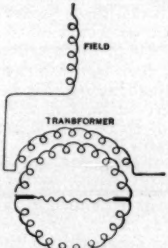


FIG. 3

pressure, and therefore the ratio of the armature pressure to the line pressure is increased. Increasing the flux in the armature also increases the flux in the magnetizing-coil in the field, and the pressures of both are increased. Therefore this increase does not improve the power-factor of the machine.

Instead of increasing the armature pressure, the pressure across the field winding may be decreased; this can be done in two ways; viz., by reducing the turns in the field coil, or by reducing flux through the coil. Reducing the flux through the field reduces the flux in the armature winding also, and therefore represents no gain; reduction in field-turns, therefore, is the feasible means of reducing the field pressure. Reduction in field-turns can be accomplished in two ways; viz., by decreasing the effective length of air-gap in the motor, and by increasing the cross-section of gap. By making the gap very small the pres-

sure across the field could be made very small compared with the line pressure, and extremely high power-factors could be obtained, whether the motor is of the straight-series or the repulsion type. Also by increasing the section of the air-gap the turns of the field can be decreased with a given total flux through the coil, and the power-factor can thus be very considerably increased. The first method, viz., decrease in gap, is limited by practical conditions which have been determined from long experience with direct-current work. It should be borne in mind when published descriptions of such motors are given that the results, as regards power-factor, generally depend upon data which are not given in the description,—such as the magnetic dimensions of the armature and field, the length of gap, etc. Therefore, a machine may be described as showing an extremely high power-factor, which may in practice not be a commercial machine, from the standpoint of American railway experience. Increasing the section of air-gap without decreasing the length of gap also improves the power-factor, but makes a larger and heavier machine, as a rule.

Both these modifications reduce the ampere-turns in the field. The direction of the improvement in the armature was shown to be in increased armature ampere-turns with a given speed. It therefore follows that almost any result desired can be obtained as regards power-factor by increasing the armature ampere-turns, and decreasing the field or exciting ampere-turns. Reference will be made to this point in considering the repulsion motor.

It should be noted that in all these motors there should be but little saturation in the magnetic circuit and but few ampere-turns expended in saturation of the iron under normal conditions. This consequent low saturation in such motors leads to certain characteristics in the torque curves which have been cited this evening as an indication of superiority of alternating-current motors over direct-current motors; namely, a torque increasing approximately as the square of the current. In fact, this superiority of torque should be charged to the low flux-density of the motor rather than to the alternating current. If direct-current motors were worked normally at as low density as the alternating-current motor, then the direct-current motor would show better torque characteristics, and would be comparable with the alternating-current motor. This claim for a better torque in the alternating-current motor compared with the direct-current motor seems to be making a virtue of a necessity.

It is evident from what has been said that the power-factor of the straight-series motor can be made anything desired, it being a question of proportion between armature and field, length of air-gap, amount of material used, etc. In practice a compromise would naturally be made among the various characteristics, and a slight reduction in power-factor is probably of less importance than a corresponding reduction in size and weight. Also large

clearance is probably of more importance than an extremely high power-factor at normal load. In practice it will be found that the armatures of such motors have a large number of ampere-turns compared with the fields, in order to obtain comparatively high power-factors with large air-gaps. The number of poles need not be made such that the product of the poles by the normal speed represents the frequency of the supply circuit; good series motors can be made, and have been made, in which the number of poles were very much larger or much smaller than represented by this relation.

Taking up next the transformer type of motors—Fig. 2; the field is in series with the primary of the transformer, the secondary of which is connected to the terminals of the motor. The speaker would call this a true series motor, although it is not a straight-series motor. In this motor the pressure across the armature can be made practically non-inductive and the pressure across the primary of the transformer will be practically non-inductive. The voltage across the field winding will have practically 90° phase relation to that across the primary of the transformer, and the magnetic field, set up by the field winding, will have a 90° relation in time to the magnetic field in the transformer, as in the repulsion motor. In this motor the voltage across the transformer will be highest at light loads and will decrease with load until zero speed is reached. At start there is lowest flux in the transformer and highest flux in the field winding. Such a motor will have speed-torque characteristics very similar to those of a straight-series motor, except as affected by the actions taking place in the transformer itself. If the transformer possesses no reactance, then at start the current in the armature should be the same as if connected as straight-series motor, and the conditions of torque at start should be the same. If the transformer has reactance, then at start the current in the armature will not be quite equal to the current which the armature will receive if coupled as a straight-series motor, assuming the transformer to have a 1 to 1 ratio. Neither will the armature current be exactly in phase with the field current; therefore the starting torque of a motor connected in this way will be slightly less than the torque of the same motor if connected in straight-series. This is on the assumption that the transformer is one proportioned for small reactance; but if the primary and secondary windings of the transformer should be on separate cores with air-gap between, then the reactances of the windings are considerably greater than in the above case. Therefore, we should expect a motor with such a transformer to give still lower torque than the straight-series with the same current supplied from the line.

In a repulsion motor the transformer is combined with the motor itself and the primary and secondary windings are upon different cores with an air-gap between. The starting conditions of such a motor as indicated above should be poorer than

the straight-series motor, or for the same starting torque somewhat greater apparent energy should be required. It stands to reason that applying the current directly to the armature winding should give greater ampere-turns and better phase relations than generating this current in a secondary circuit, and not under ideal transformer conditions. The tests which have been made, as well as the results shown in the curves of the papers given to-night indicate this. It is to be noted that the torque curve is not the same shape near the zero-speed point as the torque curve of the series motor.

Series motors and repulsion motors may be indicated in the simple form shown in Figs. 4 and 5. In the diagrams of the repulsion motor (Fig. 5), two field-poles, *FF*, are shown, and two transformer-poles, *TT*. To obtain high power-factors on such a motor the ampere-turns in *T* must be very much greater than in *F*; which means that the ampere-turns in the secondary or armature are much greater than in the exciting field, as in the series motor. The high power-factor obtained with these motors is therefore due principally to the small ampere-turns in the field and the small pressure across the field.

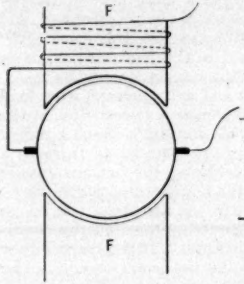


FIG. 4

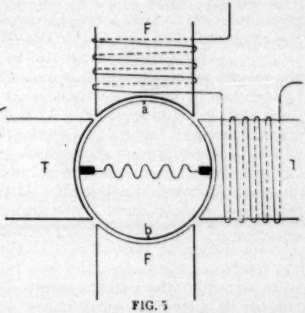


FIG. 5

For instance, with brushes set at an angle of 16°, from the primary or resultant field, the ratio of armature to exciting field-turns would be almost 5 to 1, a ratio which will also permit of extremely high power-factors in well-designed straight-series motors over wide ranges of speed. To this feature should be credited the good power-factors claimed for the repulsion motor. In either the series of repulsion type of motors, high power-factors, especially at low speeds, are directly dependent upon this fact of high ratio of armature to field, and with a high ratio high power-factors should be obtained without crediting the result to leading currents in the armature. In the diagram of the repul-

sion motors the line current indicated flows through both the field winding and the transformer winding. The primary current sets up a magnetic field in the exciting windings in phase with the line current. If it also set up a field in the transformer in phase with the line current, then the electromotive force generated in the armature winding due to rotation would have a 90° relation to the electromotive force set up by the transformer, and a correcting or magnetizing current would flow. This flow is in such direction that it corrects the relation between the two pressures in the armature by shifting the transformer magnetism one-quarter phase later than the exciting field magnetism. This armature corrective current may thus be considered as magnetizing the transformer, making the primary input to the transformer practically non-inductive; but this magnetizing or correcting current may be considered as flowing in a circuit at right angles to the field magnetic circuit, and having practically no effect on the field circuit. Therefore, as a rough approximation the exciting field may be considered to represent the wattless component of the input, and the transformer field the energy component, as in the series motor. As to the statement that the magnetizing current in the armature reduces the wattless component of the exciting field, the speaker does not accept it broadly. If this component is reduced, then another component of practically equal value is introduced somewhere else, for the power-factors obtained with such motors can be accounted for by the high ampere-turns in the armature winding, compared with the field or exciting ampere-turns. If the armature current improves the power-factor by diminishing the magnetizing or exciting field, then the curves in Figs. 1 and 4 of Mr. Slichter's paper should show it. The speaker has gone over both sets of curves calculating the wattless components from the power-factors. From this and other data in these curves, he finds that beginning near synchronous speed the wattless component in the motor goes up slightly faster than would be represented by the field excitation, assuming it to be entirely wattless. Therefore, according to these curves, the power-factors at lower speeds are not quite as good as would be obtained by a field entirely inductive and the armature entirely non-inductive, in a straight-series motor. These calculations are rather approximate, as the curves do not check at all well with each other. For instance, the output of the motor as represented by the input multiplied by the power-factor and by the efficiency, does not check with the output as represented by the product of speed by torque, in either set of curves, the discrepancies being as high as 10 per cent. In Fig. 4, for instance, either the torque or the speed is too high for the lower speeds. Checking back on this curve, using either the speed and torque or the power-factor and efficiency for determining the output, the speaker finds that the wattless component in the motor at 190 revolutions is approximately 20 per cent higher than it would be if the field excitation alone were wattless,

assuming at 440 revolutions the wattless component is represented purely by field excitation; that is, from 440 to 190 revolutions the wattless component is increased 20 per cent over that which would be represented by field excitation alone. This indicates that not only should the field excitation be considered as practically wattless, but that in addition there is a wattless component due to reactances in the armature windings.

The armature current can be split into two components, one of which is partly magnetizing and represents no torque. The other component is in phase with the field magnetism and therefore represents torque. The magnetizing or wattless element may be comparatively small, as the number of turns in the armature is relatively large, but the armature thus carries at times a slightly larger current than the straight-series motor.

A further inspection of the diagram (Fig. 5) indicates how the power-factor of the motor can be made very high at synchronous speed. At all speeds the pressure generated in the armature due to rotation in the field of F is practically equal to the pressure generated by the transformer T, thus making zero pressure across the terminals. But also at synchronous speed the pressure generated by the exciting field acting as a transformer, between the points $a\ b$, will be practically equal to the pressure generated in the winding by rotation of the winding in the transformer field. Therefore across $a\ b$ the pressure is practically zero with these conditions, but the frequency remains the same as that in the field. If now the magnetizing current be supplied across the points $a\ b$, then the required ampere-turns for magnetizing the motor can be supplied at practically zero pressure, and the turns of the external magnetizing field can be omitted. Therefore, under this condition the wattless component is practically zero and the power-factor becomes practically 100 per cent. This is the method of excitation used on certain European single-phase motors in which high power-factors are claimed for full-load running. But this method of excitation does not improve conditions at start, as the same excitation will be required at standstill, whether the excitation be supplied to the armature or to the field. Therefore this method of excitation does not help the motor at that condition of load which is the severest on the generating and transmission system. It has the advantage of omitting the field-exciting winding, but has the great disadvantage of requiring a double set of brushes on the commutator, with but half the distance between the brushes found in the straight-series or the ordinary repulsion motor. The speaker does not believe that such methods of compensation are of sufficient advantage to overcome the complications attendant upon them.

At zero speed, both the straight-series and the repulsion motors have low power-factors, and with equal losses in the motors the repulsion should have slightly lower power-factor than the series. This question of power-factor at start is largely a question of internal losses in the motor at rest, and the repul-

sion motor in individual cases may show higher than the series motor, because it may be designed with higher internal losses. The real measure of effectiveness is not the power-factor at start, but the apparent input or kilovolt-amperes at start required for a given starting torque. With equally good designs of motors, the speaker's experience is that the kilovolt-amperes will be found to be considerably less with the straight-series than with the repulsion motor, due to the fact that the current is fed directly into the armature and not by transformer action, and therefore the conditions of phase-relation and amount of current in the armature windings are more favorable. Therefore it follows that in order to have the same kilovolt-ampere input for the same starting torque, the repulsion motor should have a smaller length of air-gap than the corresponding straight-series motor, or should have a greater section of air-gap, which means greater weight of motor. This is one of the conditions which has led

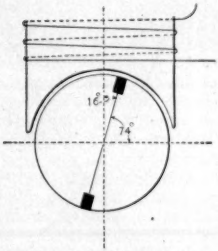


FIG. 6

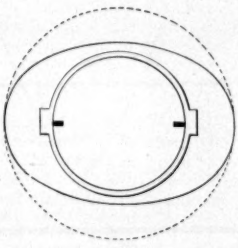
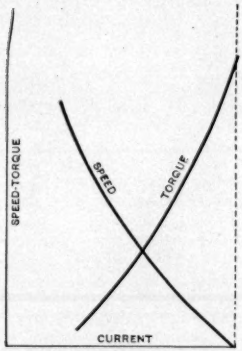


FIG. 7

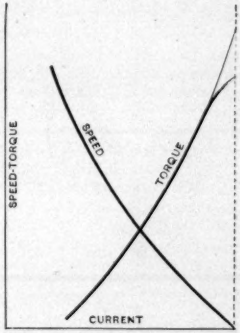
the speaker to the advocacy of the series motor rather than the repulsion motor, as he has considered this condition of starting of more importance than running; although he is satisfied that many of the running conditions of a well-designed series motor will be found in practice to be superior to those of an equally well-designed repulsion motor.

Referring again to Fig. 5, it will be noted that two fields are set up in such a motor, and that at synchronous speed these two fields are equal. In the straight-series motor there is but one field set up, the other being omitted. It is evident that the straight-series motor with the current supplied directly to the brushes can have a smaller section in certain parts of the magnetic circuit than is required for the repulsion motor, and that therefore the weight of material would be less, and the external dimensions can be less. In Fig. 7 the heavy line represents outlines of series and the dotted line those of repulsion motor; therefore, it follows that for equally good designs and same fre-

quency, the straight-series motor should be more compact, and should weigh less than the repulsion motor. It is reasonable to expect this, as the repulsion motor contains a transformer in addition to the other parts found in the straight-series motor. Furthermore, the transformer found in such a motor is one with an air-gap, and with the windings on two separate elements, and therefore cannot be so well proportioned as a separate transformer could be. Also, there is a transformer for each motor, and in a 4-motor railway equipment, for instance, there would be four transformers of smaller size against one larger transformer used with the series motor, this larger transformer having a closed magnetic circuit, and of a highly efficient design compared with the transformers in the motors themselves.



Straight Series Motor



Repulsion Motor

A further point should be taken up in the comparison of these motors; viz., the current in the coil short circuited by the brushes. This coil is a secondary to the field and the current in it is necessarily greatest at the period of strongest field. Therefore, this current will be greatest at the time of starting. If the repulsion motor and the straight series motor have the same field strength at start, then the short-circuited current should be the same in each. But as the current is fed into the armature in the repulsion motor through transformer action, it will, as a rule, be found that the starting field strength of such a motor is slightly greater and the starting armature strength slightly less for a given torque than is found in the straight-series motor having same ratio of armature to field windings. Therefore the short-circuit current at start will be somewhat larger for the repulsion motor than for the corresponding straight-series motor.

This short-circuit current may be somewhat less near full speed than in the straight-series motor, but it is not the full-speed condition which is the serious one. The short-circuit current at start is one of the most serious conditions which confronts us in alternating-current motors, and is also of great importance where there is any considerable operation on low speeds. The speaker advocates a type which he considers gives the easiest condition in this regard. This short-circuiting cannot be entirely avoided in any of the motors brought out without adopting abnormal and questionable constructions, although devices like narrow brushes, sandwich windings, etc., have been proposed. In certain foreign motors the brushes used are so narrow that they cover practically the width of one commtuator-bar. As such motors are generally built with a very large number of bars, the brushes used are extremely narrow, being approximately 0.2 inch thick at the tip. This will undoubtedly lessen the short circuiting, but simply transfers trouble to another point; a brush 0.2 inch thick is not practicable for commercial railway service; at high speeds, with only a moderately rough commutator, such brushes will be liable to chip and break; further, the brush on a street-car motor should bridge at least two bars to give good, smooth, brush operation; in practice, a 0.5 inch brush on motors of 100 hp. should be used.

The sandwich winding, which consists of two or more windings side by side, will prevent short circuiting at the brushes, but is only another way of transferring trouble to another point; it has been found in practice that it is difficult to run a sandwich winding without trouble at the commutator with direct current without a tendency to blackening and pitting the commutator, and with alternating current this tendency to pitting and burning of the bars would be equally great.

As a rule, there is little difference between the operation of repulsion and straight-series motors as regards sparking, except that the repulsion motors generally have greater current in the short-circuited coil near zero speed, and therefore show greater tendency to heat and spark. At or near synchronous speed, there appears to be very little difference in the commutation, although the speaker has never given the repulsion motor the same test of long-continued service as he has in the case of the series motor. These series motors have never shown any tendency to give trouble on the commutator, and on an exhibition car equipped with four 100-hp. motors, the commutators have never been sandpapered since the equipment has been put into service. This exhibition car is used principally for showing the accelerating properties of the motors; therefore, the speaker does not hesitate to say that the commutation of the straight-series motor will prove to be equal to that of the direct-current motor. Wide brushes are used with it, such as have been used in street-railway motors.

It is well known that with large direct-current motors, espe-

cially when operated at very high speeds, there is a tendency to flash across the commutator, or to the frame of the motor, if the field circuit be opened for a period long enough to allow magnetism to drop to zero, and then the field be closed again. In this case there is a rush of current before the field has had time to build up, and this rush of current, together with field distortion, may cause serious flashing. In the alternating-current motor, whether of the straight-series or the repulsion type, this tendency should be entirely absent. In the straight-series motor the magnetism falls to zero once in each alternation, and therefore if this tendency existed, flashing would occur continuously. Furthermore, a properly designed straight-series motor can be short circuited across the brushes without injury to the motor, and can continue to operate in this way; therefore, if the machine can be short circuited in this way, there is evidently no tendency to maintain an arc.

Returning to the subject of power-factors it should be noted that high power-factors are very frequently found in motors of low or only moderately good efficiency. This low efficiency to a slight extent explains the high power-factor in some motors, both polyphase and single-phase. Low efficiency means higher true energy expended, and with a given wattless component it means higher power-factor. It is the old problem of increasing the power-factor by wasting energy in a circuit instead of reducing the wattless component. The power-factor of any alternating-current motor can be very considerably increased by putting resistance in series with it. Instead of this resistance the internal losses of the motor may be made higher, which will accomplish the same results. The motor will therefore appear to have a higher power-factor than it really deserves, if efficiency of the motor is taken into account. If, for instance, the efficiency at 300 rev. shown in Mr. Slichter's Fig. 4 would be made as high as on direct-current motors, then the power-factors with the same magnetizing and other conditions, would have been approximately four per cent lower. This lower power-factor would not have made any harder condition on the supply circuit, but actually would have made a somewhat easier condition, as the supply system would have furnished about eight per cent less kilovolt-amperes. For lower speeds this difference in power-factor will be greater, and less for higher speeds. A high power-factor at start, obtained by the use of resistance in series with the motor by high internal losses which do not represent torque, is therefore a detrimental condition rather than a good one, as it means increased kilovolt-ampere expenditure for a given torque. This is merely given as an illustration showing that power-factor in itself is not a true indication of conditions, but must be accompanied by other data; this is not a criticism of these motors, but is a general condition, found to a greater or less extent in all alternating-current motors.

In conclusion the speaker wishes to ask a few questions in regard to some of the points brought out in these papers. One point in connection with Fig. 1, Mr. Slichter's paper, is the high power-factor of 50 per cent shown at start. The speaker would like to know how this power-factor can be so high when the motor is doing no work at this point. Is this power-factor due to high internal losses of the motor, or is an external resistance added? The speaker has tested a number of series and repulsion motors, and for motors of this capacity, as a rule, the power-factors have been somewhat lower than this; the losses in the repulsion motor for a given starting torque are always greater than in the straight-series motor, but the volt-ampere input for the same torque was also greater so that the power-factors in some cases were very nearly equal.

Also, Mr. Slichter states that the motor shown in Fig. 4 is for constant-speed running; does this mean running at a practically steady load, or is this motor intended for constant-speed work, in the sense of a shunt-wound direct-current motor?

In the comparison with the direct-current motor it is stated that the alternating-current motor remains on the controller for 16 seconds, and the direct-current motor for 25. Would it not be true that the direct-current motor could remain on the controller for a shorter time, if designed with an unsaturated field, as the alternating-current motor? Is not this a property of an unsaturated motor, rather than an alternating-current motor?

A. S. McALLISTER:—In the papers presented this evening, mention is made of the fact that the repulsion motor, when driven against its torque, acts as a generator; and when the negative speed becomes of a value such that its product with the torque exceeds the internal losses of the motor, the machine will feed energy back to the line. The analytical equations given in Mr. Steinmetz's paper furnish an explanation of the cause for this action on the part of the machine. These equations may be represented graphically by a simple diagram, and it is believed that the diagram affords a readier interpretation than do the equations.

When the rotor of the repulsion motor is stationary, measuring in truments placed in the primary circuit will indicate an apparent impedance, having power and reaction components. The power component, which will here be termed " resistance," represents the resistance effect of the primary coil, the equivalent resistance effect of the secondary circuit, and the effect of the core loss at starting. In the impedance electromotive force for one ampere—diagram of Fig. 1—this resistance, R, is represented by the line $A\,B$, while the line $B\,C$ shows the apparent reactance, X, and the cosine of the angle $C\,A\,B$ gives the power-factor of the motor at starting. When the motor operates at a speed, S, the power component of the apparent motor impedance—volts for one ampere—is increased by a certain value $P\,S$, $C\,D$ in the diagram, P being a coefficient depending upon the relative

strength of the field which causes the generation of electromotive force in the armature conductors at speed S, and hence depends upon the position of the brushes. If the apparent reactance of the coils remained of value X at all speeds, then at speed S the apparent impedance of the motor becomes :

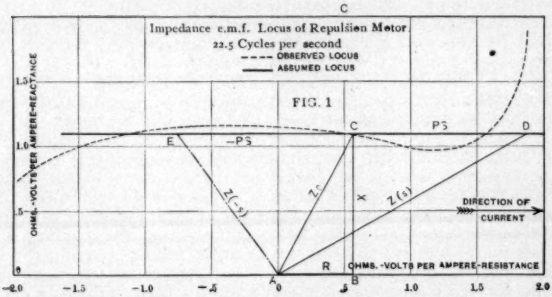
$$Z_s = \sqrt{(R+P\,S)^2+X^2}$$

and for impressed electromotive force of E the current will be

$$I = \frac{E}{\sqrt{(R+PS)^2+X^2}},$$

and the power-factor, cos θ, is

$$\cos D\,A\,B = \frac{R+P\,S}{\sqrt{(R+P\,S)^2+X^2}}$$



The power input is

$$E\,I\cos\theta = \frac{E^2\,(R+P\,S)}{(R+P\,S)^2+X^2}$$

If, independent of the change in speed of the rotor and variation of the relative values of the primary and secondary currents, the total internal losses of the motor be considered proportional to the square of the primary current, the output would be

$$I\,E\cos\theta - I^2\,R = \frac{E^2\,P\,S}{(R+P\,S)^2+X^2}$$

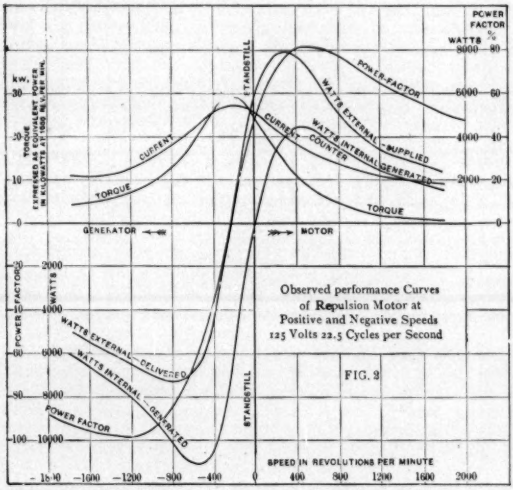
and the ratio of output to speed, the torque will be

$$I^2\,P$$

The discrepancies between the assumptions made and the physical facts involved will be evident from a study of the formation of the above equations. It will be observed that the equations here given will become identical with the approximate equations of Mr. Steinmetz if for each value used above there be substituted its equivalent as given below,

$$R = r^1$$
$$X = X \sin^2 \omega + X^1$$
$$P = X \sin \omega \cos \omega$$
$$S = a$$

An inspection of Fig. 1, or of the equations above, will reveal the fact that when S is negative and of a value such that $-PS =$



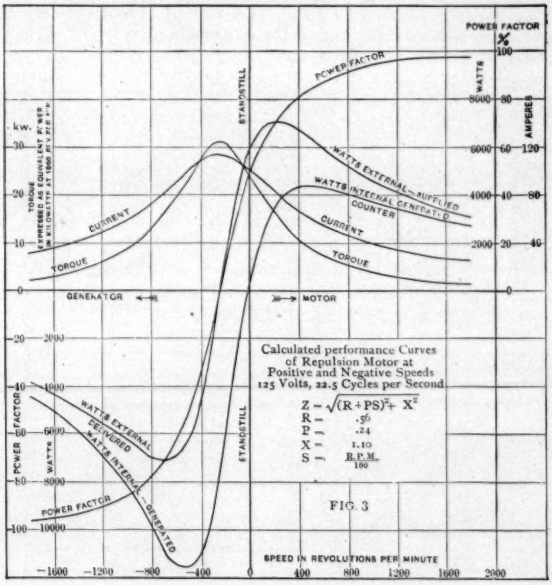
Observed performance Curves of Repulsion Motor at Positive and Negative Speeds 125 Volts 22.5 Cycles per Second

FIG. 2

R, the apparent impedance of the motor becomes X; the current is E/X and represents no energy flowing either to or from the motor; that is, the machine is operating as a generator and supplying its own losses. A further increase of negative speed causes the power component of the apparent motor impedance to take on a negative value; the power-factor becomes negative indicating that energy is flowing from the machine.

The curves of Fig. 2 show the results of tests of a certain repulsion motor while those of Fig. 3 give the calculated performance of the same motor, proper substitution having been made in the equations above.

In the discussion of the theory of the repulsion motor, Mr. Steinmetz states that the effect of the short-circuit by the brush of active coils tends to a reduction of the power-factor at high speeds; which statement may be taken as an explanation of the fact that the power-factor observed in case of high speeds is much below that calculated, as will be seen from a comparison of Figs. 2 and 3,



Calculated performance Curves of Repulsion Motor at Positive and Negative Speeds 125 Volts, 22.5 Cycles per Second

$$Z = \sqrt{(R + PS)^2 + X^2}$$

R = .56
P = .24
X = 1.10
$S = \frac{R.P.M.}{100}$

FIG. 3

The neglect of the counter-torque, due to the local current flowing in the coils under the brushes, leads also to error in assuming that the repulsion motor tends to increase indefinitely the speed of its rotor as the applied electromotive force is increased or the load decreased, since in reality experiments show that the rotor tends to reach a certain speed above which, if it be driven mechanically, it acts as a brake.

PRESIDENT ARNOLD:—Since this discussion may properly be divided and naturally divides itself into two parts, such as motor designing and the application of single-phase alternating-current

motors to railway work, it would be proper at the present time to give Mr. Steinmetz an opportunity to answer Mr. Lamme's questions and any of the other questions which have been asked.

C. P. STEINMETZ:—An alternating-current series motor, to have a reasonably good power-factor, must have a high ratio of armature magnetomotive force to field magnetomotive force; this conclusion, reached ten years ago by Mr. Eickemeyer and the speaker, is agreed to by Mr. Lamme; but there is a limit to the indefinite increase of this ratio, for the reason that the armature circuit is not really non-inductive, and there comes a point when the increase in the armature self-inductance is greater than the decrease in the field self-inductance. For the motor on which experiments were made ten years ago, this ratio was between 3.5 and 4, but very high frequencies were then used; with lower frequencies the ratio can be increased, yet there is still a limit to its indefinite increase. The fact of self-inductance in the armature explains the reason that the power-factor, calculated as Mr. Lamme calculates it—on the assumption of a non-inductive armature—gives higher values than tests show. Moreover, a brush shift of 16° is not equivalent to a ratio of 1 to 5. The two sections of the winding must be combined approximately vectorially, giving a ratio of sine 16° to sine 74°, or about 1 to 2.86, and this ratio will correspond to a lower power-factor than that obtained for a ratio of one to five.

One great advantage of the modern repulsion motor is that it uses a pole-arc of 180°, or the largest section of air-gap possible, and so secures at low speeds so high a power-factor that it is not necessary to go to speeds far above synchronism. The result thereof is a small number of poles, great number of commutator segments per pole, hence small short-circuit current in starting and running, and a low-speed commutator.

The repulsion motor has inherently such a high power-factor that a large air-gap and a high flux-density may be used, hence with heavy currents magnetic saturation is approached or passed in part of the magnetic structure, and a bend occurs in the torque curve. It is not feasible to use flux-densities quite as great as in the direct-current series motor. Further, at low speeds a point must be reached where the electromotive force of rotation becomes small compared with the electromotive force of self-induction, however small the latter may be, and below this speed the torque and current do not increase, but remain constant both in the repulsion and in the series motor.

There is no doubt that a motor designed as a series motor will give larger output and greater efficiency than the same motor used as a repulsion motor, as Mr. Lamme states; but, on the other hand, a motor designed to be repulsion motor and then run as a series motor will give the opposite result—that is, the output will be greater and the efficiency better, when operated as a repulsion motor. The reason for this is simple, and is found in the fact that a series motor must have definite polar projections,

whereas the repulsion motor uses a distributed winding, similar to that of an ordinary induction motor; hence, a low inductance is obtained with a correspondingly high power-factor. Thus the transformer feature of the repulsion motor requires a change in design, and makes a comparison of the relative performance of a particular design first, as a repulsion, and then as a series motor, meaningless.

P. M. LINCOLN:—The observations made on a car of about 40 tons, equipped with four 125-hp. alternating-current series motors, show that when in motion at speeds not above four or five miles an hour, the motor sends power back into the line on reversal as indicated by a wattmeter; the wattmeter reverses when the fields are reversed and current is on. The same characteristic has also been reproduced in shop tests, where a straight-series motor has been used as a generator to feed power back into the shop circuit to which it is connected, by driving it suitably by another motor. Another characteristic of the alternating-current series motor is that it will always build up as a direct-current generator when the reverse switch is thrown and no power applied; it acts just the same as the direct-current series motors and can be used in the well-known way as an emergency brake. In fact on one occasion, when the air brakes failed, when the car was running at high speed, this emergency brake was thrown and the car stopped very promptly, just as it would with a direct-current motor.

On page 6, referring to the speed-time curves, Mr. Slichter gives the comparative inputs for alternating and direct current, for the same car running the same distance, as 0.72 kilowatt-hours for the direct and 0.685 for the alternating current, approximately for the alternating current five per cent less energy; but the rheostatic loss for the direct-current curve amounts to approximately 15 per cent of the total curve area. He accounts for the difference of five per cent, whereas the curve areas seem to indicate that there should be a difference of at least 15 per cent, since the alternating-current motor does not include the rheostatic losses.

MR. SLICHTER:—The fact that the power-factor at starting, shown in the first curve, is as high as 50 per cent, is due to the large losses and low efficiency of this particular motor. This motor was designed some time ago, when the matter of commutation was considered to be very serious, and radical precautions were taken to prevent bad sparking at the expense of efficiency. Recent experience has shown that these precautions are not necessary and as a result it has been possible to improve the efficiency.

This low efficiency, 80 per cent, is also the cause of the small difference between the energy consumption of the alternating-current motor and the direct-current motor as the length of run increases. The low efficiency of this motor at high speeds counterbalances the saving effected by potential control during

acceleration. With a later design of alternating-current motor this efficiency would be much higher and the net saving by the use of potential control would be much more noticeable.

Referring to the motor of Fig. 4, it is intended for hauling heavy trains at constant slow speeds with few stops; in other words, long-distance freight haulage.

The fact that the controller of the alternating-current motor is cut out in so short a time, 16 seconds as against 25 for the direct-current motor, is due to the steep speed-characteristic of the motor.

In reply to Mr. Lamme's criticism of the curves, they are intended to give a general view of the characteristics of the repulsion motor and are for this purpose extended over values of current outside the working range of the motor? In this range of the curves there are several points of curvature which are difficult to check exactly, since only a few points were plotted to show the general direction.

RALPH D. MERSHON:—Mr. Slichter speaks of voltage control; what method of voltage control was used on these motors, was it such as would be used commercially? What were the comparative weights of alternating-current motors, and direct-current motors, for the same work and for approximately the same performance, either on the basis of efficiency of the motor itself or the total efficiency of acceleration? What were the relative weights of the motor and of the complete car equipment, for alternating current and direct current? Also what pressure would he use with the alternating-current motor? Mr. Slichter says these motors can be wound for high-pressure; how high? and what method of control would be used in that case? Another important point is, can the repulsion motor be so designed as to be a good repulsion motor, and yet be a pretty good direct-current motor?

It will be quite difficult to get the people responsible for existing large direct-current railway systems up to the point of changing over any considerable portion of the road at one time. The change can be much more easily accomplished if it can be made more or less gradually as, for instance, by changing outlying sections first, and this can be done if the motor is such as can be used on both the direct-current lines and alternating-current lines. As a matter of interest, what was the number of poles of the motors represented by these curves?

A. H. ARMSTRONG:—The curves given on the first three pages of Mr. Slichter's paper refer to four-pole motors and the curves in Fig. 4 to a six-pole motor, all operating at 25 cycles. Mr. Mershon stated the matter about right when he asked if a repulsion motor could be designed to operate well on alternating current and at the same time be operative on direct current. It is not possible to get equally good results with both alternating current and direct current, but a good alternating-current motor will give sufficiently good results when operated on direct current to enable a car so equipped to operate over direct-current lines.

The repulsion motor can be wound for 2000 or 3000 volts direct, without the use of transformers; but experience in operating with such pressures on railway equipments is yet to be had, and it is not known how much deterioration will be produced by the constant jarring and crystallizing of the insulation. Should it become too expensive to maintain high-pressure motor winding, it will be necessary to resort to the use of transformers; with the high-pressure motors, control will be effected by either a compensator or by the insertion of resistance, as in the present direct-current control.

If a car stops once in five miles, the small difference in efficiency in starting between rheostatic and pressure control would have practically no effect upon the general efficiency of the system as a whole. A gain of one or two per cent in the average car energy would not compensate for the additional complication. It will be entirely feasible to consider 2000 or 3000 volts on the field of the repulsion motor without any intervening apparatus, but this, as stated before, will be largely determined by commercial operation. The repulsion motor having no metallic connection between field and armature, and thus not being in any way limited by commutation can have its field wound for as high-pressure as operating conditions will permit.

No definite figures can be given for the relative weight of alternating-current and direct-current railway motors. The capacity of direct-current motors has been very carefully worked out during the past few years; but the alternating-current motor is not in commercial operation, it has not been possible to obtain experimental data upon its relative capacity and hence its weight and size compared with the direct-current motor must remain an open question for the present. The alternating-current motor will undoubtedly weigh somewhat more than the direct-current motor for the same service performed, but the percentage increase cannot be stated with any degree of accuracy at the present time.

In a high-pressure motor system using trolley pressure directly on the field, the control system should not weigh much more than that required for direct-current motors. If, however, a low-pressure motor is used with the high-pressure trolley, it will require the installation of a step-down transformer, which weight must be considered in addition to the regular control system. The average energy consumption of some of our suburban cars reaches as high as 75 to 100 kw., and the addition of a 100-kw. transformer of either the oil-cooled or the air-blast type will constitute an appreciable addition to the weight of the car equipment.

PRESIDENT ARNOLD:—The question of the destruction of the insulation or crystallization of the metal used in the construction of high-pressure motors has been pretty thoroughly answered in practice by the use of such high-pressure motors abroad; the line in Italy, using 3000-volt motors, has been operated for two

or three years and no such objection has been used against it. If abroad they can build motors which can run successfully under that pressure, we should be able to do the same.

C. P. STEINMETZ:—The present alternating-current motor, either series or repulsion type, has a somewhat lower efficiency and is somewhat heavier than the direct-current series motor, but this difference is less than would be expected; the principles involved in the design of the two types are quite different, so that no direct comparison of one with the other can be made.

There is no inherent reason why the efficiency and weight of the alternating-current motor should not be on a par with those of the direct-current motor, after the type has been further developed.

ROBERT LUNDELL:—A possible reason why the efficiency of the alternating-current motor is not as great as that of a direct-current motor is because the hysteresis losses and the eddy currents are bound to be larger in the alternating-current motor. In the alternating-current motor we have to take care of the eddy currents and hysteresis losses in an apparatus which must weigh more much than the armature of the direct-current motor. As the hysteresis or core losses are due to the cycles per second, the density of the magnetism and also to the weight, it seems to me that the weight is bound to be greater in the surrounding frame, that is, the field magnets which surround the armature of the alternating-current motor. Is not that one reason why the efficiency of the alternating-current motor can not possibly be as high as that of the direct-current motor?

O. S. LYFORD, JR.—In a direct-current motor, we can get 200 horse power in a motor on the truck, or 400 horse power in a pair of wheels on one truck; will Mr. Slichter say whether the 175 horse power motor described on page 6 is of such dimensions that it could be placed on the ordinary interurban car-truck with 33 or 36 inch wheels? How large an alternating-current motor can we get for a 33 or a 36 inch wheel? In other words, what is our limit at the present time in the motor-car field?

W. I. SLICHTER:—That motor is designed for locomotive work and would not be of dimensions to go under a car having 33 inch wheels.

The ideas on this subject are developing very rapidly; one could not say that a 100 horse power motor could be placed there, but perhaps it would not be advisable to say that a larger motor could not be.

B. G. LAMME:—The Westinghouse Electric and Manufacturing Company is building 150-hp. motors which will go in on 33-inch wheels closely; easily on 36-inch wheels It has been determined that we can put 200-hp. motors on 36-inch wheels. That is one limit.

PRESIDENT ARNOLD:—If you gentlemen who build railroads will call for the motors, you will probably get them.

H. A. WAGNER:—Does not the repulsion type of motor take

somewhat more copper in the field than the series motor? and in reversing the former, is it proposed to move the brushes or to feed the current into the stator at a different point?

C. P. STEINMETZ:—The repulsion motor can be reversed by changing the point of entrance of the current to the primary wires, without changing the brushes; thus the primary winding may have current brought to it at several different points in the repulsion motor, and the brushes need not be shifted. The relative amounts of copper in the armature and field may be varied to some extent to suit the design, but there is no essential difference in the proportions of material.

[COMMUNICATED AFTER ADJOURNMENT BY B. G. LAMME.]

In the discussion of the papers of Messrs. Steinmetz and Slichter, the writer indicated in a very general way some of the reasons which led him to the advocacy of the straight-series motor. Some of the more important of these reasons can be classified as follows:

Lighter weight with a given output and given performance.

Larger air-gap with a given input at start.

Less short circuiting at commutator at start, with a given starting torque.

Ability to operate the motor on various pressures by simply using taps on the transformer which supplies the motors. For instance: a motor can be run at 3000 volts on one part of the line, or at 500 volts on another part by simply feeding the trolley circuit into a different point in the transformer. Also the transformer can be readily stepped-up to a slightly higher pressure, thus allowing a higher normal speed and ability to make up for delays. This general arrangement will be of especial importance in heavy railway work, now represented by steam service.

The motor will be normally wound for low pressures. It has been claimed that the advantage of the alternating-current motor for railway work is that it can be wound for high-pressure, but, on the other hand, it enables us to wind the motor for low-pressure. Taking into account the troubles that are found with direct-current motors at 500 and 600 volts, the writer believes that one of the greatest advantages of the alternating-current motor is that the motor itself can be wound, if desired, for much lower than 500 volts, while a pressure of 2000 or 3000 can be supplied from the trolley. The writer does not believe that a pressure of 3000 should be supplied directly to the motor. This judgment is based partly on European experience with high pressures on railway motors. A motor wound for this pressure will necessarily be heavier than one wound for low-pressure, even if the same type of motor is retained. Therefore, if low-pressure is to be used on the motor with a step-down transformer on the car, then the writer considers that the repulsion type of motor, being naturally heavier than the straight-series, is used at a great disadvantage, as the equipment contains not only transformers in the motors themselves, but also an external transformer.

A further condition, applying to all alternating-current motors, is the fact, already published, that there is an active pressure between turns on the field of motors. This is of considerable importance considering the overload capacity of such motors. In the direct-current motor a short circuit can occur between two or more field-turns without immediately disabling the motor. In the alternating-current motor a similar short circuit will disable the motor. Therefore if the alternating-current motor is to meet the same conditions of service as the direct-current motor, it will require much more insulation in its windings than that required in the direct-current motor, and this in turn means that the motor must be either increased in size, or must be wound for lower pressure. The writer therefore believes that whether straight-series or repulsion motors are used, the motor should be wound for a relatively low pressure.

Mr. Steinmetz's suggestion that these conclusions in regard to relative weights of straight-series and repulsion motors were based on the use of series-motors operated as repulsion motors, just as his conclusions were based on repulsion motors operated as series motors, is incorrect; for these conclusions have been drawn from designs of straight-series and of repulsion motors, each type being proportioned for its own special method of operation; the writer has designed a number of motors of each type, and a repulsion motor of 125 horse power capacity was constructed for the purpose of investigation.

Mr. Slichter states that the discrepancies in the curves of Figs. 1 and 4, are due probably to the complicated nature of the calculations of these curves; but his paper states that the curves of Fig. No. 1 " are taken from tests on a 60-hp. 25-cycle, 500-volt motor." If these curves were obtained entirely by calculation, there could be wide discrepancies which might have been overlooked, if the final results were not checked with each other.

Mr. Steinmetz states that one advantage of the repulsion motor over the series motor lies in the fact that the magnetic leakage should be less, due to the distributed windings of the primary; but he overlooks the fact that in a series motor designed for high power-factor, the magnetic leakage of the exciting field-winding can be made extremely low; the leakage of the two motors will be practically equal if the primary fields are wound for equal pressure; if, however, the repulsion motor field is wound for high-pressure, with a comparatively small number of slots, the magnetic leakage will be higher than on the low-pressure motor, and will therefore be higher than on the series motor. Mr. Steinmetz's opinion of straight-series motors may be based on data obtained about ten years ago. There has been considerable improvement in the art since then, and the development of this motor for commercial railway service has undoubtedly led to proportions and forms of construction not contemplated ten years ago.

[COMMUNICATED AFTER ADJOURNMENT BY CHAS. F. SCOTT.]

The papers and their discussion are notable on account of several omissions. The subject under consideration, namely, the single-phase railway motor, brought forth no question as to the practicability of the single-phase system; it elicited no mention of the polyphase railway motor; it led to no questions regarding the matter of commutation of alternating currents.

It must be borne in mind that it is less than a year and a half since the first authoritative announcement of the single-phase railway motor was made. The announcement was the occasion of much surprise and many were sceptical as to the question whether the single-phase motor was practicable or even possible. The practicability of the single-phase motor is now received without question, and it is tacitly accepted that the single-phase motor and the single-phase system are factors of very serious consequence in the immediate extensions of railway work.

At the Buffalo Convention of the INSTITUTE in 1901, a paper was read by Mr. Berg in the discussion of which Mr. Steinmetz and the writer took part. We concurred with the conclusions of the paper that the polyphase motor was not suited for railway work, and that the efforts of European engineers to introduce polyphase motors for railway work were not along lines which would prove a general solution of the railway problem. There were criticisms at that time and subsequently in the technical press setting forth the backwardness of American engineers and indicating the forward steps which were being made in Europe in the introduction of alternating current for railway work. Our contention, however, was not against the alternating current but against the induction motor for railway work. It is notable that since it has been stated that there is an American single-phase motor, European engineers have taken up the development of single-phase apparatus, indicating thereby the shortcomings of the polyphase railway motor. It is significant that the polyphase motor did not come up for consideration in the general discussion of the single-phase motor in connection with the Steinmetz and Slichter papers.

There was some disappointment in connection with a meeting of the INSTITUTE a little over a year ago at which the single-phase series motor was presented, because certain specific data regarding the design of the motor, particularly in connection with its commutation, were not given in connection with the general engineering presentation of the single-phase system. There seemed to be an idea that there was a mysterious something which had been introduced into the motor as a panacea for the evils of alternating-current sparking, which was being withheld. The papers now under discussion do not deal with the particulars of commutation. The general statement that the single-phase motor, whether of the repulsion type or of the straight-series type, does commutate and commutate successfully, was accepted without question and without awaking any apparent curiosity

as to the methods or devices by which it is accomplished. This illustrates how quickly a new thing passes from the category of that which is doubtful and incredible to that in which it is an accepted fact, from which important commercial results are expected to follow as a matter of course.

The present papers and their discussion deal almost entirely with the presentation of one type of single-phase motor and a comparison bet veen it and a second type. The motor, however, is but one feature, although the fundamental one, cf the single-phase system. It is the general system which the motor makes possible, as was intimated in the remarks of President Arnold, which is the thing of real consequence. The significant result of the introduction of this motor is not the motor itself, but it is the use of alternating current throughout the whole system; it is the omission of synchonous converter sub-stations with synchronously running apparatus, rendering the present distribution system one which is inefficient, cumbersome, and sensitive in operation; it is the use of high-pressure and the resulting economy in transmission; it is the many advantages found in the construction of controllers for heavy alternating current over those for heavy direct current; it is the advantages which come from pressure control instead of resistance control; it is the readiness with which energy may be returned to the circuit by the alternating-current motor having pressure control (which is not practicable with the direct-current motor having pressure resistance control); it is the lessened concentration of energy in alternating-current circuits in case of short circuit; it is the safety to the car equipment on account of the non-flashing of alternating-current motors, thus avoiding one of the serious difficulties in direct-current motors on large equipments; it is the freedom from electrolysis, and, in short, it is the superiority shown by the alternating current over the direct current in practically every element from generator shaft to motor shaft, by which the limitations found in the direct-current system are removed and a new field, the bounds of which are not yet determined, is opened in the development of electric railway service. The outcome of the synchronous converter which has been so great a factor in the railway extensions of the past half dozen years has been the suburban and interurban railway. The single-phase motor opens the way to a new system which has in it elements which promise far greater developments than those which followed the introduction of the synchronous converter.

[COMMUNICATED AFTER ADJOURNMENT BY B. A. BEHREND.]

The writer wishes again to illustrate by a few diagrams the close resemblance between the alternating-current series motor with a compensating coil for the cross-ampere turns of the armature on the one hand and the repulsion motor on the other. Fig. 1 shows the straight-series motor; Fig. 2 shows the series motor with compensating-coil. In order to obtain a high power-

factor it is necessary, as has also been pointed out by Mr. Steinmetz and Mr. Lamme, to make the armature magnetomotive force considerably greater than the field. This is indicated in Fig. 2 by showing the field-coil F with few turns and the compensating-coil C with a large number of turns; instead of passing

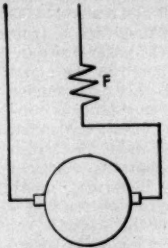


FIG. 1
Straight Series Motor

the field current through the compensating-coil C, this coil can be short-circuited itself as illustrated in Fig. 3. The main current also can be passed through the compensating-coil C in series with the field F and the armature be short-circuited on itself, thus making the armature the secondary and the compensating-coil

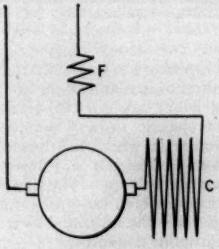


FIG. 2
Series Motor with Compensating Coil

the primary instead of the reverse, as in Fig. 3. The coils F and C may be replaced by one resultant-coil R, leading to the repulsion motor Fig. 5.

From the above considerations, it follows that, with very close approximation, the torque, power-factor, and the

efficiency of the compensated series motor represented in Figs. 3 and 4 are equal to those of the repulsion motor Fig. 5. There is no reason why the power-factor of the repulsion motor should be better than the power-factor of the compensated series motor

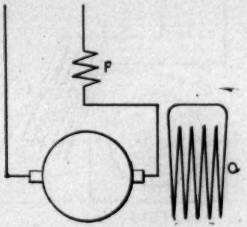


FIG. 3

Series Motor with Armature as Primary and Compensating Coil Short-circuited as Secondary

of Fig. 2; and Mr. Steinmetz's Fig. 4 showing the comparison between a repulsion motor and an Eickemeyer compensated series motor is therefore most misleading. If the motors are

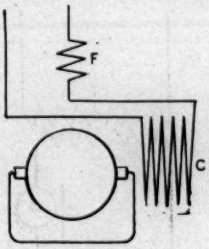


FIG 4

Series Motor with Compensating Coil as Primary and Armature Short-circuited as Secondary (Repulsion Motor)

designed with the same degree of care they should have approximately equal power-factors at all speeds. Mr. Steinmetz says: "The secondary current of the transformers, however, lags slightly less than 180° behind the primary current; that is, con-

sidering it in the reversed direction, is a leading current with regard to the primary current. The current in the armature in Fig. 3 is therefore a leading current with respect to the line current and so not only does not add an additional lag, but reduces the lag caused by the self-induction of the field-exciting coil."

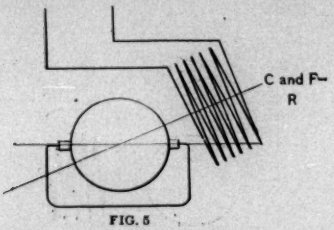


FIG. 5

Repulsion Motor Field and Compensating Coil Combined

Mr. Lamme says on this point:

"In either the series or repulsion type of motors, high power-factors, especially at low speeds, are directly dependent upon this fact of high ratio of armature to field, and with a high ratio, high power-factors should be obtained without crediting the result to leading currents in the

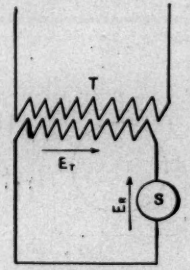


FIG. 6

E_T represents e.m.f. of transformation
E_R " " " rotation

armature."

The fact is, however, that the secondary current in the repulsion motor, beyond a certain speed of the armature, leads in respect to the primary electromotive force as in a transformer in which the secondary is working on self-induction and

capacity, or on self-induction and an over-excited synchronous motor. The primary current, however, is always a lagging current in regard to its impressed electromotive force. The repulsion motor is like a combination of a transformer with a synchronous motor, the electromotive force of which is coincident in

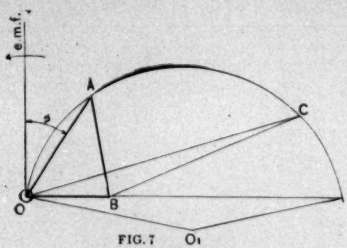


FIG. 7

OB Magnetizing current
OA Primary current
AB Secondary current
OC Primary starting current
O Centre of circle

phase with the primary current (Fig. 6). The electromotive force of transformation E_T and the electromotive force of rotation, E_R (the latter is proportional to the speed of rotation) are in opposition and give a resultant electromotive force, which

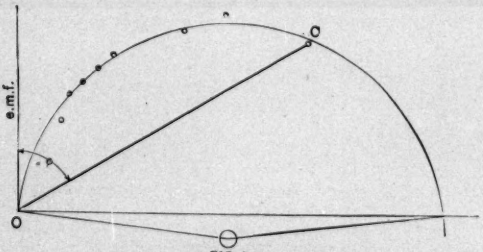


FIG. 8

Vector diagram corresponding to Mr. Slichter's Curves of Repulsion Motor
O C Starting current

produces the current through the ohmic resistance of the short-circuited armature. With Fig. 6 in mind it is easy to see that the secondary current leads the primary electromotive force at certain speeds of the armature. The polar diagram brings out

this point even more clearly. Fig. 7 represents the vector-diagram of the repulsion motor with a small resistance in the armature. This is the theoretical vector-diagram of the repulsion motor as developed a few months ago by Messrs. Osnos and Blondel; the writer's tests, as well as Mr. Slichter's curve, agree closely with this diagram; the polar diagram corresponding to Mr. Slichter's curves is represented in Fig. 8.

As has also been pointed out by Messrs. Osnos and Blondel, the torque of the repulsion motor, in contradistinction to the series motor, vanishes at a finite speed, hence the repulsion motor is not so likely to run away as the series motor. For the sake

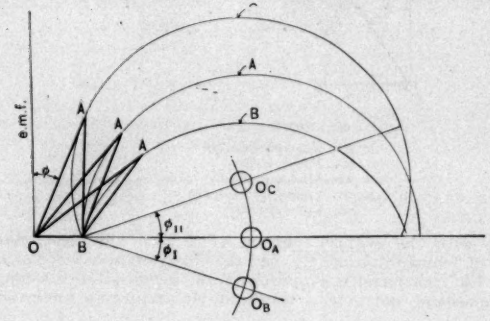


FIG. 9

O B Primary magnetizing current
O A Primary current
A represents locus of vector of primary current with resistance in
B " " " " " " " " inductance in } secondary
C " " " " " " " " capacity in }

of comparison, Fig. 9 shows the vector diagram for the polyphase induction motor with (*A*) resistance in the secondary, (*B*) reactance in the secondary, (*C*) capacity in the secondary. (See Chapter VIII. of the writer's book "The Induction Motor." from which these diagrams are taken.) It is clear that the compensated series motor represented in Fig. 2 can be made with a better power-factor than the compensated series motors represented in Figs. 3 and 4, and hence the compensated series motor in which the main current passes through the compensating-coil, everything else being equal, has a higher power-factor than the repulsion motor, instead of a lower power-factor, as Mr. Steinmetz seems to think.

Mr. Lamme's remarks are most interesting and instructive, but the writer believes Mr. Lamme is not correct in stating that the

power-factor of the repulsion motor is lower than that of the series motor, a conclusion which, by the way, is diametrically opposed to that at which Mr. Steinmetz arrived. Mr. Lamme assumes that the inductance of the armature is negligible, and then draws a parallel between the straight-series motor and the repulsion motor as illustrated by Fig. 4 in this communication. Granting the assumption of a non-inductive armature (which is by no means permissible), Mr. Lamme's conclusions are right, but on that assumption the compensated-series motor would give no better power-factor than the straight-series motor, which is obviously untrue. Mr. Lamme's reasoning and his conclusions have therefore to be modified, and instead of stating as he does that the power-factor of the repulsion motor is lower than the power-factor of the series motor, it should be stated that the power-factor of the repulsion motor is slightly lower than that of the compensated-series motor, but considerably higher than that of the straight-series motor. From the English patent specification, it appears that Mr. Lamme's motor is a compensated-series motor, corresponding to Fig. 3 in this communication.

In order to obtain high power-factors, it is necessary to design both the series motor and the repulsion motor on the same principles that have been found of importance in the design of induction motors. The successful series motor, however, has to be built with defined poles. Very good repulsion motors can be built for 60 cycles, and maximum power-factors of 90 to 95 per cent can be obtained even on small machines for comparatively low speeds. Such motors have very excellent series characteristics and can be used wherever the direct-current series motor is satisfactory.

By W. S. Franklin.—(*Communicated after Adjournment*):—On May 19, 1903, the writer had the privilege of debating some points in alternating-current theory with Mr. Steinmetz before the Schenectady Branch of the Institute. During the visit which preceded this debate, the writer discussed the theory of the repulsion motor, at length, with Mr. Steinmetz. The writer had very recently worked out the theory of the repulsion motor, outlined below, and his results are in substantial agreement, with Mr. Steinmetz's; but, knowing that Mr. Steinmetz had been working at the matter much longer, the writer urged him to present his work to the Institute, at an early date.

At the time of the conference, it was clear to both Mr. Steinmetz and the writer that the ideal theory as given in Mr. Steinmetz's paper, and as outlined below, did not take account of the very considerable distortion of the electromotive force wave due primarily to the fact that the two fluxes ϕ' and ϕ'' (see below) are not harmonically distributed around the periphery of the

machine. A first approximation to a correct theory is based upon the assumption that the fluxes are harmonic both in time and in space. A second approximation would be to consider the departure of the fluxes from harmonic space distribution, basing the calculations of this departure upon the first approximate solution by taking account of the magnetomotive forces generated in the several parts of the windings by the harmonic current values arrived at by the first approximation. Whether a third approximation, based upon calculated departures of the fluxes from harmonic variation in time, would be required for practical purposes, could be perhaps more cheaply answered by making a motor and comparing actual tests with second approximate calculations than by the arithmetical determination of the magnitude of the corrections introduced by the third approximation.

The development of the theory (first approximation) of the repulsion motor following is essentially the same as that of Mr. Steinmetz; it is given here because of the slightly different point of view, and because it is an example of the right-handed notation ($r+jx$ instead of $r-jx$.)

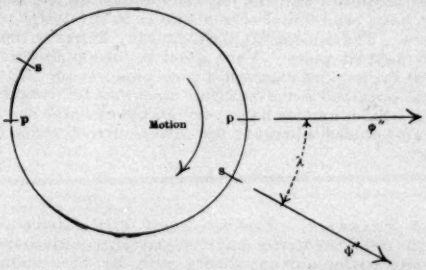


FIG. 1.

2. OUTLINE OF THEORY OF REPULSION MOTOR.

Fig. 1 shows the axis of commutation $s\,s$ of the armature (secondary-tap axis), and the corresponding axis, $p\,p$, in the primary member of a repulsion motor. The primary current produces an alternating flux ϕ' at full primary frequency f' in the direction of the primary-tap axis, and the secondary or armature current produces an alternating flux ϕ'' at full primary frequency in the direction of the secondary-tap axis.

Let e' be the value of and E' the complex expression for primary impressed voltage.

f' the primary frequency.

i' the value of the primary current. The primary-current vector is taken as the reference axis and therefore i' is also the complex expression for the primary current.

ϕ' the value of the alternating flux due to the primary current i'.

θ' the phase-angle between E' and i', positive when E' is ahead of i'.

Then

$$\phi' = k\, i' \tag{1}$$

in which k is the flux produced by unit primary current; and

$$E' = e' (\cos\theta' + j \sin\theta') \tag{2}$$

Furthermore, let Z be the number of conductors in the primary winding; the number of secondary conductors being assumed to be the same for the sake of simplicity.

r_1 the resistance of the primary.

x_1 the reactance value of magnetic leakage at primary frequency.

f'' the speed of the armature in cycles per second.

i'' the value of secondary current and I'' its complex expression.

r_2 the secondary resistance.

θ'' the phase-angle between i' and i'', positive when i'' is ahead of i'.

ϕ'' the value of the alternating flux due to the secondary current i'', and Φ'' its complex expression.

Then

$$\Phi'' = k\, I'' \tag{3}$$

in which k has sensibly the same value as in equation (1); and

$$I'' = i'' (\cos\theta'' + j \sin\theta'') \tag{4}$$

To establish the general equations of the repulsion motor we must consider (*a*) the voltages induced in the primary. Placing the sum of such induced voltages equal to $-E'$ gives one equation; and (*b*) the voltages induced in the secondary. Placing the sum of such induced voltages equal to $+r_2 I''$ gives another equation.

Equation of Primary Voltages.—The total impressed primary voltage is made up of the following parts:

(*a*) The part $(r_1 + j x_1)\, i'$ used to overcome primary resistance and magnetic leakage reactance.

(*b*) The part $+j \cdot \dfrac{\phi' Z f'}{\sqrt{2}}$ used to balance the electromotive force induced in the primary by the pulsating flux ϕ'.

(*c*) The part $+j \cdot \dfrac{\Phi'' Z f'}{\sqrt{2}} \cdot \cos\lambda$ use to balance the electromotive force induced in the primary by the pulsating flux Φ''.

Therefore:

$$E' = (r_1 + j x_1)\, i' + j \cdot \frac{\phi' Z f'}{\sqrt{2}} + j \cdot \frac{\Phi'' Z f'}{\sqrt{2}} \cdot \cos\lambda \tag{5}$$

Equation of Secondary Voltages.—The total electromotive force induced in the secondary is used to overcome secondary resistance; it is therefore equal to $r_2 I''$, and it consists of the following parts:

(*a*) The part $-j \cdot \frac{\phi' Z f'}{\sqrt{2}} \cdot \cos \lambda$ produced by the pulsations of the flux ϕ'.

(*b*) The part $-j \frac{\Phi'' Z f'}{\sqrt{2}}$ produced by the pulsations of the flux Φ''.

(*c*) The part $+ \frac{\phi' Z f''}{\sqrt{2}} \cdot \sin \lambda$ produced by the motion of the secondary relative to the flux ϕ'.

Therefore:

$$r_2 I'' = \frac{\phi' Z f''}{\sqrt{2}} \cdot \sin \lambda - j \cdot \frac{\phi' Z f'}{\sqrt{2}} \cdot \cos \lambda - j \cdot \frac{\Phi'' Z f'}{\sqrt{2}} \qquad (6)$$

Equations (5) and (6), together with the equations of definition (1), (2), (3), and (4), are the fundamental equations of the repulsion motor. The assumptions upon which these equations rest and the extent to which these assumptions deviate from the conditions which really exist in a repulsion motor are discussed later. Three things only need be said to clear up the derivation of equations (5) and (6); namely, (*a*) only that component of a flux which is parallel to a tap-axis produces electromotive force by pulsation; (*b*), only that component of a flux which is at right angles to a tap-axis produces electromotive force by motion; and (*c*), all induced electromotive forces involved in equations (5) and (6) are of the same frequency f'. This is due to the fact that the electromotive forces induced in the secondary are referred to the stationary tap-axis $S\,S$ *Fig.* 1; the electromotive force (or current) in a given moving secondary wire may be thought of as having a frequency f'', while its amplitude varies at frequency f'. This is equivalent to the superposition of two genuine alternating electromotive forces of which the frequencies are $f'+f''$ and $f'-f''$ respectively.*

Substituting the values of ϕ', Φ'', E', and I'' from equations (1), (2), (3), and (4) in equation (5), we have:

$$e' \cos \theta' + j\, e' \sin \theta' = r_1 i' + j\, x_1 i' + j \cdot \frac{k Z f'}{\sqrt{2}} \cdot i'$$

$$+ j \cdot \frac{k Z f'}{\sqrt{2}} \cdot \cos \theta'' \cos \lambda \cdot i''$$

* $2 [\cos \omega' t] \cdot \cos \omega'' t = \cos (\omega' + \omega'') t + \cos (\omega' - \omega'') t.$

$$-\frac{k\,Z\,f'}{\sqrt{2}}\,.\,\sin\theta''\cos\lambda\,.\,i'' \qquad (7)$$

Substituting the values of ϕ', Φ'', E' and I'' from equations (1), (2), (3) and (4) in equation (6) and we have:

$$r_2 i''\cos\theta''+j\,r_2 i''\sin\theta''=\frac{k\,Z\,f''}{\sqrt{2}}\,.\,\sin\lambda\quad i'$$

$$-j\,.\,\frac{k\,Z\,f'}{\sqrt{2}}\,.\,\cos\lambda\,.\,i'-j\,\frac{k\,Z\,f'}{\sqrt{2}}\,.\,\cos\theta''\,.\,i''+\frac{k\,Z\,f'}{\sqrt{2}}\,.\,\sin\theta''\,.\,i'' \qquad (8)$$

Let

$$\frac{k\,Z\,f'}{\sqrt{2}}=a$$

$$\frac{k\,Z\,f''}{\sqrt{2}}=b$$

Then, separating real and imaginary parts, equation (7) becomes

$$\left.\begin{aligned} e'\cos\ \theta' &= r_1 i'-a\sin\theta''\cos\lambda\,.\,i'' \\ e'\sin\ \theta' &= x_1 i'+a\,i'+a\cos\theta''\cos\lambda\,.\,i'' \end{aligned}\right\} \qquad (9)$$

and equation (8) becomes:

$$\left.\begin{aligned} r_2\cos\ \theta''\,.\,i'' &= b\sin\lambda\,.\,i'+a\sin\theta''\,.\,i'' \\ r_2\sin\ \theta''\,.\,i'' &= -a\cos\lambda\,.\,i'-a\cos\theta''\,.\,i'' \end{aligned}\right\} \qquad (10)$$

The torque, power-output, power-intake, power-factor, and efficiency curves of the repulsion motor plotted on speed-base (f'') may be calculated from equations (9) and (10) as follows:

In the first place, r_1, e', a, and x_1 are known from the design of the motor and from the given value and frequency of the primary voltage.

In the second place, λ and r_2 may be each varied at will, and therefore the curves are to be plotted for each of a series of arbitrarily assigned values of λ and r_2. In the third place, f'' may be taken as the independent variable, upon which the tracing of the curves depends, and the values of torque, power-output, power-intake, etc., calculated for various assigned values of f''.

Thus, from an assigned value of f'' the value of b is known. From this, together with the known values of r_1, e', a, and x_1, and the chosen values of λ and r_2, the values of i', i'', θ', and θ'' are determined by equations (9) and (10). Then for the given speed f'' we have:

power-intake $= e' i' \cos\theta'$
power-factor $= \cos\theta'$
power-losses $= i'^2 r_1 + i''^2 r_2 +$ core losses.*

*Eddy current and hysteresis losses are to be calculated independently of the above ideal theory, from the known value of $\phi', \Phi'', \lambda, f'$ and f'' See following discussion of Mr. Steinmetz's paper.

power-output	= power-intake minus losses
torque	= power-output $\div 2\pi f''$
efficiency	= power-output $\div$ power-intake.

The above outline of the method of calculating the characteristic curves of the repulsion motor is sufficiently simple as a matter of theory but it is quite laborious as a matter of fact; and therefore certain of the terms of low value may be advantageously discarded in the final algebraic expressions for i', i'', b', and θ''.

3. Discussion.

(*a*) It may be worth while to point out the correspondence between Mr. Steinmetz's quantities Z and x (see page 19 of Mr. Steinmetz's paper), and the quantities which the writer represents by a and b, especially inasmuch as Mr. Steinmetz seems not to have specified the meaning of his symbol x.

Mr. Steinmetz's Z is identical with a, and Mr. Steinmetz's x (see equation (4), page 19) is equal to $f'/f'' \times b$.

When magnetic leakage is not very great, an ampere-turn, whether on the primary or secondary, produces sensibly the same amount of flux through the secondary, and in this case Mr. Steinmetz's Z and x are identical, if, as is assumed for the sake of simplicity, the primary and secondary have the same number of conductors.

(*b*) Mr. Steinmetz seems to say on page 14 that inductance-reactance in the secondary of a transformer becomes capacity-reactance in its effect upon the primary! The fact is that the decrease of lag of the primary current of a transformer due to load on the secondary is essentially the same effect as the decrease of lag of total current when a circuit of comparatively low inductance is connected in parallel with a highly inductive circuit.

Aside from difference in size or in design, it is not clear why Mr. Steinmetz's Fig. 3 should have a higher power-factor than his Fig. 2 (this matter is considered in detail under *c*) and even if Mr. Steinmetz's apparent statement regarding the relative power-factors of Figs. 2 and 3 is correct, his explanation is not convincing.

The series motor provided with a Ryan compensating winding (*c*) to annul armature reaction is, when operated by alternating current, identical in its action to the repulsion motor, save in one respect, which is mentioned under *d*.

Consider, for example, Mr. Steinmetz's Fig. 5, which is equivalent to his Fig. 6. This constitutes a repulsion motor. The same structure with all three windings connected in series would be a series motor with a Ryan compensating winding. Let us consider the correspondences between the two machines on the assumption that coil resistances are zero; that magnetic leakage is zero; and that magnetic reluctance of core is zero.

Under these conditions the compensating winding A_2 and the armature winding together constitute an ideal transformer (zero

resistance, zero magnetic leakage, and zero magnetic reluctance*) so that the current in the short-circuited armature of Fig. 5 is exactly equal in value and opposite in phase to the main current in winding A_2, and the electromotive force induced in the armature by motion is transformed to or exactly reproduced in winding A_2, except that its phase is reversed.

Now, the reversal of phase is merely a matter of reversing connections so that the current induced in the armature is exactly the current which would flow through the armature if it were properly connected in series with the two field windings; and the electromotive force which opposes the flow of current through the two field windings A_1 and A_2 in Fig. 5 is exactly the electromotive force which would oppose the flow of current if the armature were properly connected in series with the two field windings.

Under the above-mentioned ideal conditions, the motor action of the device is exactly the same, its power-factor is the same; in fact, everything is the same, with the one exception mentioned under *d*, be the device connected as a repulsion motor or as a series motor.

So much for the ideal case; but what are the effects of coil resistances, magnetic leakage and core reluctance? These effects vitiate the motor action and they vitiate motor action more when the device is connected as a repulsion motor than when the device is connected as a series motor. This may be made clear by the following simple considerations:

When all the windings are connected in series the current is the same in all and the armature current is exactly in phase with the torque-producing flux. When the armature is short-circuited and the armature current produced by transformation from the winding A_2, then (*a*) the armature current (secondary) is slighty less in value than the main current (ratio of primary to secondary turns equal to unity) on account, primarily, of core reluctance; and (*b*) the armature current differs in phase slightly from the main current and therefore from the torque-producing flux on account, primarily, of coil resistances and magnetic leakage.

Therefore, other things being equal, the torque is lessened on account of coil resistances, magnetic leakage, and core reluctance.

(*d*) The one difference between the compensated-series motor and the repulsion motor is the above-described transformer action and the production of cross-flux (M_2 in Mr. Steinmetz's paper) associated therewith.

This transformer action is, however, under ideal conditions entirely independent of motor action, whereas under practical conditions this transformer action, itself incomplete, detracts from the action of the structure.

*It would be well if the "practical man" realized that once in a while, at least, the "theoretical man" sets forth ideal conditions in order that a practical matter may be made simple enough for the practical man to understand.

When the device (Fig. 5) is connected as a compensated series motor, no cross-flux is produced and the cross-reluctance of the core may be made high, perhaps with advantage; certainly with saving of material.

(*e*) There is one point wherein the repulsion motor has an advantage over the compensated-series motor, and in regard to which the writer agrees with Mr. Steinmetz. This is in the matter of hysteresis and eddy-current losses in the armature core.

In the compensated series motor the armature is subjected to reversals of magnetization and the hysteresis and eddy-current losses are high.

In the repulsion motor the effect of the cross-flux is to produce a resultant magnetization of the armature core, which rotates at synchronous speed. This rotating magnetization is elliptical below and above synchronous speed of the armature, and circular at synchronous armature speed, so that in the repulsion motor the hysteresis loss in the armature core is large at standstill; it decreases to zero at synchronous speed, and increases again at speeds above synchronism.

The writer does not, however, agree with Mr. Steinmetz in his statements concerning the variation with speed of hysteresis loss in the armature core of the series motor. This loss is large at standstill, it decreases to about $\frac{1}{2^{11}}$ as great a value at synchronous speed and increases again at speeds above synchronism.

By B. G. Lamme.—(*Communicated after Adjournment*):—It appears that there is a possible misunderstanding of the use of the term "straight-series" as applied by the writer to one class of single-phase motors. By this term the writer means motors in which the armature and field windings are all directly in series, and in this class is included motors with compensating windings in the poles. In the discussion of Mr. Steinmetz's paper the writer referred to the armature as being practically non-inductive and the field as being the inductive element. For best proportions such a motor would naturally be of the compensated type, and the writer's discussion was based primarily upon "straight-series" motors having compensating windings, although no direct statement to that effect was made. The series motor without compensating winding would undoubtedly have considerably higher armature self-induction than the compensated motor, and would naturally have lower power-factor.

[COMMUNICATED AFTER ADJOURNMENT BY COMFORT A. ADAMS.]

Note:—Vectors are indicated by bold-faced capitals.

In connection with Mr. Steinmetz's very neat and compact treatment, the following graphical representation may be of interest.

Assume that the reluctance of the main magnetic circuit is constant and the same in all radial directions. Reduce all secondary quantities to primary turns, and at first, neglect primary resistance and core loss; these may be taken into account later.

Referring to Fig. 1, which is a time vector diagram:

$\mathbf{I}_1$ = primary current and m.m.f.

$\mathbf{I}_2$ = secondary current and m.m.f.

$\mathbf{I}_1' = \mathbf{I}_1 \cos\beta$ = the component of the primary m.m.f. in the secondary axis, and

$\mathbf{I}_2' = \mathbf{I}_2 \cos\beta$ = the component of the secondary m.m.f. in the primary axis, where

β = the angle between the two axes, determined by the position of the brushes.

$\mathbf{J}_1' = \mathbf{I}_1 + \mathbf{I}_2 \cos\beta$ = the resultant m.m.f. along the primary axis;

$\boldsymbol{\Phi}'_1$ = the corresponding flux.

$\mathbf{E}'_1 = j x_0 \mathbf{J}'_1$ = the corresponding primary e.m.f. in quadrature with $\boldsymbol{\Phi}'_1$, where x_0 is the exciting reactance.

$\overline{\phi_1' \phi_1}$ = the primary leakage flux, in phase with and proportional to I_1:

$\overline{E'_1 E_1} = j \mathbf{I}_1 x_1$ = the corresponding primary drop due to the leakage reactance, x_1;

$\boldsymbol{\Phi}_1$ = total primary flux: (1)

Draw $\overline{J'_1 A}$ parallel and proportional to $\overline{\phi_1' \phi_1}$, then $\overline{O A} = \mathbf{J}_1$ is the current which would produce the flux $\boldsymbol{\Phi}_1$ in the main magnetic circuit. It is the total equivalent exciting current in the primary axis.

$\mathbf{E}_1 = j x_0 \mathbf{J}_1$ = total primary inductive e.m.f., proportional to ϕ_1, and in quadrature therewith.

$\overline{E_1 E_0} = \mathbf{I}_1 r_1$ = the ohmic drop in primary, and

$\mathbf{E}_0$ = the impressed e.m.f. For the present $I_1 r_1$ will be neglected and E_1 will be assumed equal to E_0, and *constant*

ϕ_1 and J_1 are then constant for constant E_1.

$\mathbf{J}_2' = \mathbf{I}_2 + \mathbf{I}_1 \cos\beta$ = resultant m.m.f. along secondary axis;

$\boldsymbol{\Phi}_2'$ = the corresponding flux; and

$\mathbf{E}_2' = -j x_0 \mathbf{J}'_2$ = the corresponding induced e.m.f.;
$\overline{\phi_2' \phi_2}$ = the secondary leakage flux; and
$\overline{E_2' E_2} = -j \mathbf{I}_2 x_2$ = the corresponding e.m.f.
Φ_2 = the total secondary flux;
$\mathbf{J}_2$ = the equivalent exciting current.
$\mathbf{E}_2 = -j x_0 \mathbf{J}_2$ = the corresponding e.m.f. (1a)
$\overline{O S} = \mathbf{I}_2 r_2$ = secondary ohmic drop.
$\overline{S T} = j \mathbf{I}_2 x_2 = \overline{E_2 E'_2}$ = secondary leakage drop, where r_2

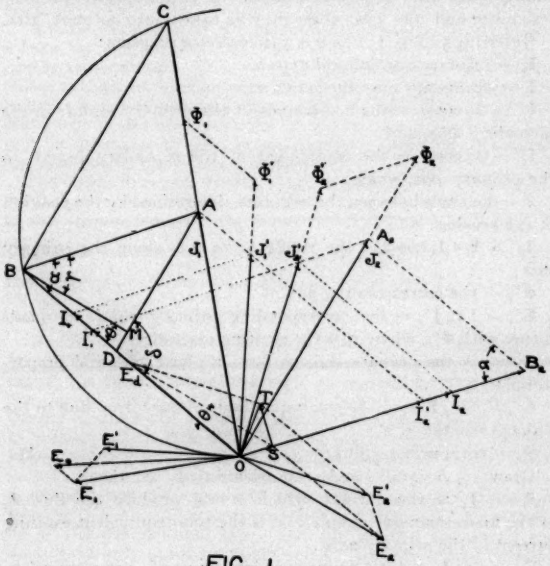


FIG. 1.

and x_2 are the secondary resistance and leakage reactance respectively.

Let ϕ_d = the dynamic flux perpendicular to the secondary axis and produced entirely by the component $\mathbf{I}_1 \sin \beta$, of the primary m.m.f., since the secondary m.m.f. is perpendicular to that direction and contributes nothing. Then the dynamic e.m.f. induced by the rotation of the armature through this flux will be:

$\mathbf{E}_d = a\, x_0 \mathbf{I}_1 \sin\beta$, in phase with $\mathbf{I}_1$, where a is the speed in per cent of synchronism. (2)

$$\mathbf{E}_d + \mathbf{E'}_2 = \overline{O\,T} = \mathbf{I}_2 \mathbf{Z}_2 \text{ or}$$
$$\mathbf{E}_d + \mathbf{E}_2 = \overline{O\,S} = \mathbf{I}_2 r_2 \text{ and}$$
$$a\, x_0 \mathbf{I}_1 \sin\beta - j\, x_0 \mathbf{J}_2 = \mathbf{I}_2 r_2 \qquad (3)$$

Complete the parallelograms $\overline{O\,I'_2\,A\,B}$ and $\overline{O\,I_1'\,A_2\,B_2}$.

Let: $\mathfrak{R}_0$ = reluctance of main magnetic circuit:
$\mathfrak{R}_1$ = reluctance of primary leakage circuit;
$\mathfrak{R}_2$ = reluctance of secondary leakage circuit.

Then: $$\mathfrak{R}_0 \equiv \frac{J'_1}{\phi'_1} = \frac{J_1}{\phi_1} = \frac{J'_2}{\phi'_2} = \frac{J_2}{\phi_2} = \frac{\overline{A\,J'_1}}{\phi_1\,\phi'_1} = \frac{\overline{A_2\,J'_2}}{\phi_2\,\phi'_2}$$

$$\mathfrak{R}_1 \equiv \frac{I_1}{\phi'_1\,\phi_1} \text{ and } \mathfrak{R}_2 \equiv \frac{I_2}{\phi'_2\,\phi_2}$$

$$\frac{\overline{O\,B}}{I_1} = \frac{\mathfrak{R}_0+\mathfrak{R}_1}{\mathfrak{R}_1} = \frac{x_0+x_1}{x_0} = \nu_1, \text{ the primary leakage coefficient,} \qquad (4)$$

and

$$\frac{\overline{O\,B_2}}{I_2} = \frac{\mathfrak{R}_0+\mathfrak{R}_2}{\mathfrak{R}_2} = \frac{x_0+x_2}{x_0} = \nu_2, \text{ the secondary leakage coefficient.} \qquad (4a)$$

Then

$$\overline{O\,B} = \nu_1 \mathbf{I}_1 \qquad (5)$$

and

$$\overline{O\,B_2} = \nu_2 \mathbf{I}_2 \qquad (5a)$$
$$\mathbf{J}_1 = \nu_1 \mathbf{I}_1 + \mathbf{I}_2 \cos\beta \qquad (6)$$
$$\mathbf{J}_2 = \nu_2 \mathbf{I}_2 + \mathbf{I}_1 \cos\beta \qquad (6a)$$

Draw $\overline{A\,D}$ parallel to $\mathbf{J}_2$ and $\overline{B\,M}$ perpendicular to $\overline{A\,D}$. In the triangle $\overline{O\,A\,D}$, $\overline{O\,A} = \mathbf{J}_1$ is constant, and angle $\overline{O\,D\,A} = \delta = 90° + \theta$, where θ is the small angle between $\mathbf{E}_d$ and $\mathbf{E}_2$. It may be easily determined as follows: Express $\mathbf{I}_1$ in terms of $\mathbf{J}_2$, it is:

$$\mathbf{I}_1 = \mathbf{J}_2 \frac{r_2 + j\, x_0 \nu_2}{r_2 \cos\beta + a\, x_0 \nu_2 \sin\beta} \qquad (7)$$

$$\text{then } \tan(\mathbf{J}_2 \mathbf{I}_1) = \cot\theta = \frac{x_0 \nu_2}{r_2}$$

$$\text{and } \tan\theta = \frac{r_2}{\nu_2 x_0} = \frac{r_2}{x_0 + x_2} \text{ which is constant.} \qquad (7a)$$

Therefore $< \delta = 90° + \theta =$ constant, and the point $\overline{D}$ will always fall on the arc of a circle through $\overline{O\ D\ A}$.

Draw $\overline{B\ C}$ parallel to $\overline{D\ A}$ and $\mathbf{J}_2$; then $O\ C/O\ A = O\ B/O\ D$ but $O\ B = \nu_1 I_1$

and $$\overline{O\ D} = \overline{O\ B} - \overline{B\ D} = \nu_1 I_1 - \frac{I_1 \cos^2 \beta}{\nu_2} = \nu_1 I_1 \left[1 - \frac{\cos^2 \beta}{\nu_1 \nu_2}\right]$$

Therefore $$\frac{O\ C}{O\ A} = \frac{1}{1 - \frac{\cos^2 \beta}{\nu_1 \nu_2}} = \frac{1}{\sigma}$$

where

$$\sigma = 1 - \frac{\cos^2 \beta}{\nu_1 \nu_2} \text{ is the leakage factor.} \tag{8}$$

Then $$\overline{O\ C} = \frac{\overline{O\ A}}{\sigma} = \frac{J_1}{\sigma} \text{ and is constant.} \tag{9}$$

Thus, since angle $\overline{O\ B\ C} = \delta =$ constant, the locus of $\overline{B}$ is the circular arc $\overline{O\ B\ C}$. But $\overline{O\ B} = \nu_1 I_1$ and $\overline{B\ A} = I_2 \cos \beta$, *i.e.*, proportional to I_1 and I_2 respectively. The triangle $\overline{O\ B\ A}$ thus shows clearly the relative magnitudes and phases of I_1 and I_2, for the various positions of B on the arc $\overline{O\ B\ C}$.

Speed.

The different positions of $\overline{B}$ correspond to different speeds and to different values of the angle γ. There is therefore some relation between the speed a and the ang'e γ. But as the latter is the angle between $\mathbf{E}_2$ and $\mathbf{I}_2$ its value is readily found, thus; express $\mathbf{I}_2$, in terms of $\mathbf{E}_2$; it is

$$\mathbf{I}_2 = \mathbf{E}_2 \frac{\cos \beta + j\, a \sin \beta}{r_2 \cos \beta + a\, x_0 \nu_2 \sin \beta} \tag{10}$$

$$\text{then} \quad \tan (\mathbf{E}_2 \mathbf{I}_2) = \tan \gamma = a \tan \beta \tag{11}$$

which is directly proportional to the speed, or

$$a = \frac{\tan \gamma}{\tan \beta} \tag{11a}$$

It should be noted that the scale according to which $\tan \gamma$ is a measure of the speed, depends upon the brush angle β.

There are several linear methods of representing the speed, but the angular method is more convenient for the present purpose.

Referring to Fig. 2, extend $\overline{B\,M}$ until it intersects the large circle at $\overline{N}$; draw $\overline{N\,C}$, $\overline{N\,A\,B_0}$ and $\overline{O\,B_0}$. Then

$<\overline{N\,C\,O} = <\overline{N\,B_0\,O} = \theta$, being inscribed in the same arc $\overline{O\,N}$.

$<\overline{N\,B\,C} = 90°$. ∴ . $\overline{N\,C}$ is a diameter of circle $\overline{O\,B\,C}$.

Draw $\overline{O\,b}$, making angle θ with $\overline{O\,A}$; then b is the center of the circle $\overline{O\,B\,C}$.

As B moves around to the right, γ and the speed decrease, until $\alpha = \theta$, when γ and the speed are zero. Thus B_0 corresponds to $\alpha = 0$, $\overline{O\,B_0}$ is proportional to the primary and $\overline{B_0\,A}$ to the secondary short-circuit current.

TORQUE.

The dynamic power is

$$P_d = E_d\ I_2 \cos\alpha \qquad (12)$$

where

$$\alpha = \gamma + \theta \qquad (13)$$

The torque, in synchronous watts is then,

$$T = (1/\alpha)\ E_d\ I_2 \cos\alpha \qquad (14)$$

or substituting from equation (2)

$$T = x_0\, I_1\, I_2 \sin\beta \cos\alpha \qquad (14a)$$

Draw $\overline{A\,H}$ perpendicular to $\overline{O\,B}$, then

$$\overline{H\,B} = I_2 \cos\beta \cos\alpha$$

and since

$$\overline{O\,B} = \nu_1\, I_1$$

$$T = \overline{O\,B} \times \overline{H\,B}\ \frac{x_0 \tan\beta}{\nu_1} * \qquad (15)$$

Thus the torque is proportional to the product of $\overline{O\,B}$ and $\overline{H\,B}$ for any given brush position, but the constant of proportionality varies with the brush position.

The locus of the point H is the semicircle $\overline{O\,H\,A}$, since $< \overline{O\,H\,A} = 90°$.

The Torque Efficiency, or torque per ampere, may be readily obtained by substituting for I_2 in eq. 14a, its value in terms of I_1; thus,

*NOTE.—A very simple and elegant method of representing the torque by a single line, is given by Dr. Th. Lehmann, in *L'Eclairage Electrique*, for February 13, 1904.

$$T = I_1^2 \frac{x_0 \sin\beta\cos\beta}{\nu_2}\left[1 - \frac{r_2}{r_2^2+\nu_2^2 x_0^2}(r_2 + \nu_2 x_0 a \tan\beta)\right]$$

or, since r^2_2 is ordinarily negligible with respect to $\nu_2^2 x_0^2$

$$T = I_1^2 \frac{x_0 \sin\beta\cos\beta}{\nu_2}(1 - a\tan\theta\tan\beta) \qquad (16)$$

Again, $a \tan\theta \tan\beta$ is very small at ordinary speeds and we have approximately:

$$T = I_1^2 \frac{x_0 \sin\beta\cos\beta}{\nu_2} \qquad (16a)$$

i.e., the torque is approximately proportional to the square of the current. It also appears from this last equation that the *maximum torque efficiency* corresponds to a brush angle $\beta = 45°$. This, however, is not the angle corresponding to the maximum torque or the highest power-factor, as will appear later.

MAXIMUM SPEED.

As B moves to the left the torque decreases and speed increases until $\overline{B\,H}$, and thus the torque vanishes at B_m, which corresponds to the maximum possible speed. At this point $\alpha = 90°$ and $\gamma = 90° - \theta$; but since θ is, under normal conditions, very small, $\tan\gamma$ and thus the speed, is very large, much beyond the safe mechanical limit as well as that of commutation.

POWER-FACTOR.

The angle ϕ (between E_1 and I_1) decreases steadily from standstill to maximum speed, as B moves from B_0 to B_m, and the power-factor increases accordingly, The factors which affect ϕ for any given speed will be considered later.

Eliminating between equations (1) (2) (3) and (6);

$$\mathbf{I}_1 = \frac{\mathbf{E}_1}{x_0}\,\frac{\nu_2 x_0 - j r_2}{\nu_1 r_2 + a x_0 \sin\beta\cos\beta + j x_0 \sigma \nu_1 \nu_2}$$

$$\tan\phi = \frac{\dfrac{r_2^2 + \sigma x_0^2 \nu_2^2}{x_0 \nu_2 (1-\sigma)} + a r_2 \tan\beta}{r_2 + a x_0 \nu_2 \tan\beta} = \frac{\tan\theta + \dfrac{\sigma}{\tan\alpha}}{1-\sigma} \qquad (17)$$

As θ is normally very small, we have approximately

$$\tan\phi = \frac{\sigma}{(1-\sigma)\tan\gamma} = \frac{\sigma}{a(1-\sigma)\tan\beta} \qquad (17a)$$

which is inversely proportional to the speed. Mr. Steinmetz has given one explanation (page 25) why the power-factor does not in fact increase with the speed beyond a certain limit, but reaches a maximum and then falls off.

Primary Power.

$P_1 = E_1 I_1 \cos \phi$, is proportional to the altitude of the triangle $O B A$, (since E_1 is assumed constant), and its maximum value occurs when B is at the top of the circle $\overline{O B C}$.

The circle diagram[1], Fig. 2, is thus a great help in picturing the general relations of the several variables (currents, power-factors, speed, torque, and power), and the manner of their variation

It is also very useful in tracing the effect of changes in the constants of the motor, as will appear from what follows.

Impressed Electromotive Force.

Since each line of the diagram is proportional to E_1, other things being equal, the currents will vary directly with E_1 and the torque and power with E_1^2.

Primary Resistance.

If $\mathbf{E}_1$ is assumed constant, $\mathbf{E}_0$ $(= \mathbf{E}_1 + \mathbf{I}_1 r_1)$, the real impressed e.m.f., must vary slightly; and since the locus of the extremity of $\mathbf{I}_1$ is a circle, the locus of the extremity of $\mathbf{I}_1 r_1$ is a similar circle, as indicated in Fig. 2.

But practically, E_0 would be kept constant and E_1 would vary, decreasing slightly as I_1 increases, while the whole diagram shrinks in the same proportion. Otherwise the effect of the primary resistance is to throw E_0 more nearly into phase with I_1 and thus to increase the power-factor.

Core Losses.

To take account of the core losses, a small energy component must be added to the primary current, which not only increases I_1 but advances its phase and increases the power-factor.

Effect of Variation of Constants.

Before proceeding, it will be convenient to assemble and transform a few of the equations which show the relations between the several constants and the diagram.

1. Much the same diagram has been developed by Osnos, *Elektrotechnische Zeitschrift*, October 29, 1903, and Blondel, *L'Eclairage Electrique*, November and December, 1903, but by quite different methods, and from different starting points.

$$\overline{OA} = J_1 = \frac{E_1}{x_0} \tag{18}$$

$$\overline{OC} = \frac{\overline{OA}}{\sigma} = \frac{E_1}{\sigma x_0} \tag{19}$$

$$\sigma = 1 - \frac{\cos^2\beta}{\nu_1 \nu_2} = \frac{x_0^3 (1-\cos^2\beta) + x_0 (x_1+x_2) + x_1 x_2}{x_0^3 + x_0 (x_1+x_2) + x_1 x_2}$$

$$= \frac{\mathfrak{R}_1 \mathfrak{R}_2 (1-\cos^2\beta) + \mathfrak{R}_0 (\mathfrak{R}_0+\mathfrak{R}_1+\mathfrak{R}_2)}{\mathfrak{R}_1 \mathfrak{R}_2 + \mathfrak{R}_0 (\mathfrak{R}_0+\mathfrak{R}_1+\mathfrak{R}_2)} \tag{20}$$

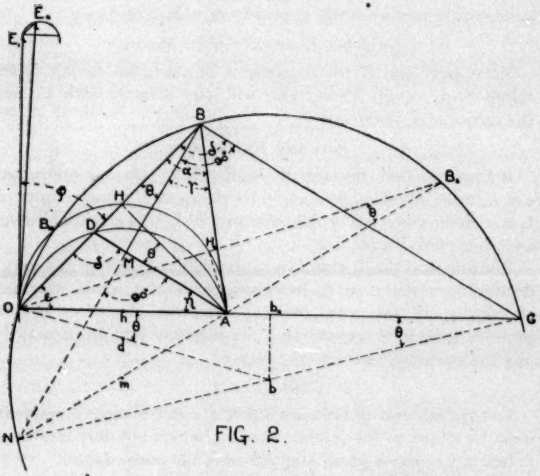


FIG. 2.

$$\sigma_0 = 1 - \frac{1}{\nu_1 \nu_2} = \frac{x_0 (x_1+x_2) + x_1 x_2}{x_0^2 + x_0 (x_1+x_2) + x_1 x_2} = \frac{\mathfrak{R}_0 (\mathfrak{R}_0+\mathfrak{R}_1+\mathfrak{R}_2)}{\mathfrak{R}_1 \mathfrak{R}_2 + \mathfrak{R}_0 (\mathfrak{R}_0+\mathfrak{R}_1+\mathfrak{R}_2)} \tag{21}$$

$$\overline{OB} = \nu_1 I_1 = I_1 \frac{x_0 + x_1}{x_0} \tag{22}$$

$$\overline{BA} = I_2 \cos\beta \tag{23}$$

$$\tan\theta = \frac{r_2}{\nu_2 x_0} = \frac{r_2}{x_0 + x_2} \tag{24}$$

$$\tan\gamma = a\tan\beta \tag{25}$$

$$T = \overline{OB}\,.\,\overline{HB}\,\frac{x_0\tan\beta}{\nu_1} \tag{26}$$

SECONDARY RESISTANCE.

A change in r^*_2 affects neither $\overline{OA}$, $\overline{OC}$, nor the relation between the speed and $\tan\gamma$, but it does alter the position of the center b of the circle $\overline{OBC}$, since

$$\overline{b_0 b} = \frac{\overline{OC}}{2}\tan\theta = r_2\frac{E_1}{\sigma\nu_2 x_0^2} \tag{27}$$

i.e., an increase in r_2 means a proportional dropping down of b from $\overline{OC}$, and when $r_2 = 0$, b lies at b_0, the circle always passing through O and C. In Fig. 3, several resistance circles are drawn, corresponding to resistances from zero to seven.

Consider the movement of B corresponding to a change of r_2 under constant speed, *i.e.*, with γ constant.

Then $< \overline{ABC} = 90° - \gamma$, and is constant, and B will move on a circular arc $\overline{ABC}$, whose center lies on the perpendicular erected at the centre of $\overline{AC}$.

Imagine B to move along one of these constant-speed circles until $\overline{BAC} = 90°$, then $\overline{BC}$ will be a diameter of circle $\overline{BAC}$, and the intersection of $\overline{BC}$ with the perpendicular $\overline{m_0 m}$ will be the center of the constant speed circle in question. Moreover, since $\overline{ABC} = 90° - \gamma$, $< \overline{ACm} = \gamma$. Thus, $\overline{m_0 m}$ is directly proportional to the speed a corresponding to the circle in question.

$$\overline{m_0 m} = \overline{m_0 C}\tan\gamma = J_1\frac{1-\sigma}{2\sigma}a\tan\beta = \frac{E_1}{2x_0}\frac{a\tan\beta}{\frac{\nu_1\nu_2}{\cos^2\beta} - 1} \tag{28}$$

When $a = 0$, the center falls to m_0. Several constant speed circles are shown in Fig. 3.

If B falls within the semicircle $\overline{OA}$, the torque is negative, if it falls within the semicircle $\overline{AC}$, the speed is negative, and points outside of semicircle $\overline{OC}$ correspond to negative values of r_2.

*It is understood that r_2 includes the total secondary resistance, internal and external.

Therefore, it is evident that for operation as motor, B must fall within the area enclosed by these three semicircles.

The variation of torque and power-factor with speed and secondary resistance can be readily traced on diagram, Fig. 3.

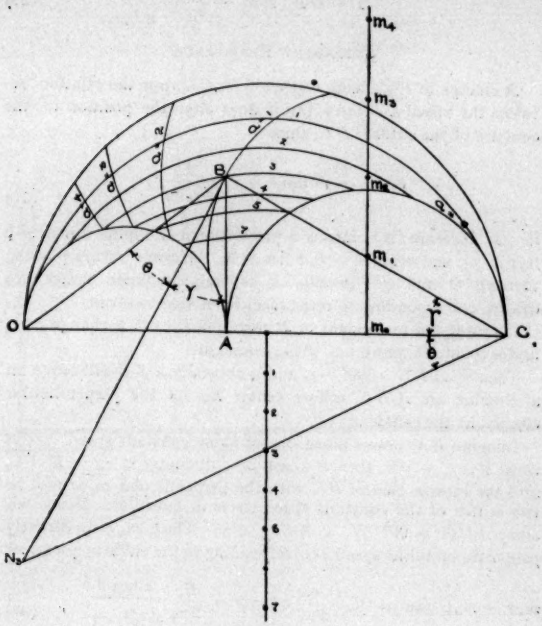


FIG. 3.

Leakage Reactance.

Leakage in primary and secondary have for the most part the same general effect, except that ν_1 alone effects the scale according to which $\overline{O\,B}$ represents I_1 (eq. 22), and also the torque scale (eq. 26); while ν_2 alone effects $\tan\theta$ (eq. 24). But ν_1 is constant in any given machine, varying only slightly in different types,

whereas ν_2 which includes any external reactance connected between the brushes, may have a wide variation.

Consider then, a variation in ν_2 or x_2. Assume that there is no external resistance between brushes, then r_2 may be neglected without seriously affecting the general results of the analysis.

Referring to the equations of page 70, a change in ν_2 or x_2 does not affect $\overline{O\,A}$, it does affect σ and thus $\overline{O\,C}$. In Fig. 4, several $\overline{O\,B\,C}$ circles are drawn, corresponding to values of x_2, varying from $+4$ to -4, 0.4 being the normal value for the machine in question.

As x_2 decreases, passes through zero and increases negatively, σ decreases and passes through zero, and the point C moves out to infinity on the right and comes back on the left.

As r_2 was neglected, $< \overline{O\,B\,A} = \gamma$, and if the speed be maintained constant while x_2 varies, the locus of B will be a circle $\overline{O\,A\,B}$ whose center lies on the perpendicular at the center of $\overline{O\,A}$. If q_1 is the center of the constant speed circle corresponding to $a = 1$, then the $< \overline{O\,q_1\,A}$ = twice the $< \overline{O\,B_1\,A}$ and $\overline{O\,q_1\,p} = \gamma_1$. Then,

$$\frac{\overline{O\,p}}{\overline{p\,q_1}} = \tan\gamma_1 = a_1 \tan\beta$$

and

$$\overline{p\,q_1} = \frac{\overline{O\,p}}{a_1 \tan\beta} = \frac{E_1}{2\,a_1\,x_0 \tan\beta} \qquad (29)$$

The effect of the secondary resistance will be to flatten the constant-speed circles slightly.

Air-Gap.

An increase of air-gap means an increase in $\mathfrak{R}_0$, a decrease in x_0, and an increase in $\overline{O\,A}$. An inspection of equation (20) shows that since $(1 - \cos^2\beta)$ is ordinarily a small fraction, and since $\mathfrak{R}_1\,\mathfrak{R}_2$ is large as compared with $\mathfrak{R}_0$ $(\mathfrak{R}_0 + \mathfrak{R}_1 + \mathfrak{R}_2)$, σ falls only a little short of being proportional to $\mathfrak{R}_0$. Therefore, $\overline{O\,C}$ $(= \overline{O\,A} \div \sigma)$ is nearly independent of the air-gap.

The air-gap also affects the primary-current scale slightly (eq. 22), the torque scale to a greater extent (eq. 26), and $\tan\theta$ (eq. 24).

It is seen from (eq. 16) that the current corresponding to any given torque is otherwise approximately proportional to $\sqrt{\frac{1}{x_0}}$, or

to $\sqrt{R_s}$; thus, to double the gap would add about 40% to I_1, and produce a considerable decrease in the power-factor. This is easily traced on the diagram by imagining $\overline{OA}$ to increase, without affecting $\overline{OC}$.

BRUSH POSITION.

Here, again, it is desirable to neglect r_2 in order to get a simpler view of the effect of changing β.

$\overline{OA}$ is unaffected, but $\overline{OC}$ increases with decreasing β.

The secondary-current scale (eq. 23), the speed scale (eq. 25), the torque scale (eq. 26) and the torque efficiency (eq. 16) are also dependent upon β.

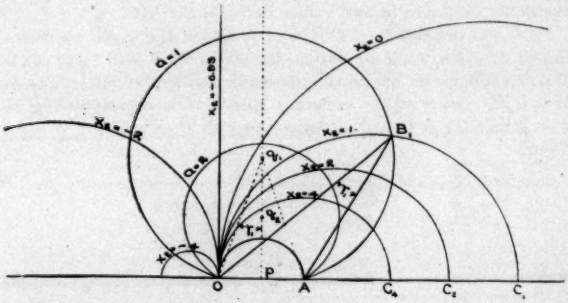


FIG. 4.

The locus of the point B with varying β and constant speed, is not a simple curve, but has been drawn in on Fig. 5 for several speeds. Circles are also shown for values of β varying from 0° to 90°.

Since all losses have been neglected, the input is equal to the output, and for any given speed the altitude of the point B is proportional to the torque; *i.e.*, if B moves along one of the constant-speed curves, the maximum torque for that speed corresponds to the highest point of the speed curve under consideration.

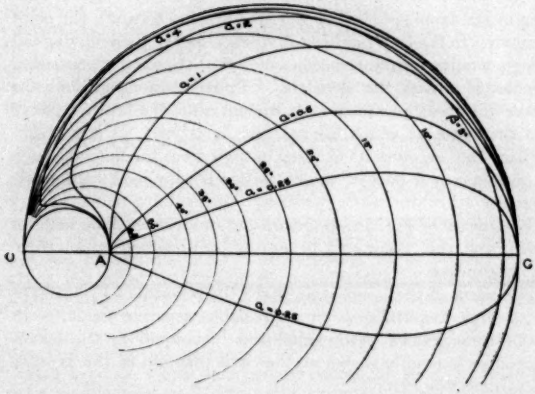
It will be observed that this maximum torque occurs with a very small brush angle β for high speeds, decreasing to 45° at standstill. This maximum torque and maximum output are obtained at the expense of a low power-factor and excessive

current, and are far beyond normal operation, except at reduced voltage. It is somewhat analogous to the maximum output obtained from a direct-current motor by weakening its field until the counter e.m.f. equals one-half of the impressed e.m.f.

The best value of β is that which gives the highest power factor; it is determined as follows, from (eq. 17a):

$$\tan \phi = \frac{\nu_1 \nu_2 - \cos^2 \beta}{a \sin \beta \cos \beta} \tag{30}$$

FIG. 5.



Placing the derivative of tan ϕ with respect to cos β equal to zero and solving

$$\cos \beta = \sqrt{\frac{1}{1+\sigma_0}} \tag{31}$$

which is independent of the speed.

Substituting this in (30) gives for the minimum value of tan ϕ

$$\tan \phi_m = \frac{2\sqrt{\sigma_0}}{a} \nu_1 \nu_2 \tag{32}$$

If $\nu_1 = \nu_2 = 1.1$, $\beta_m = 23°$ and $\cos \phi_m = .703$
If $\nu_1 = \nu_2 = 1.05$, $\beta_m = 17°$ and $\cos \phi_m = .803$
} for $a = 1$

The less the leakage the smaller the angle β_m for maximum power-factor. Eq. (32) shows clearly the factors upon which the maximum power-factor depends.

Figs. 3, 4, and 5 together with the accompanying equations, give a fairly clear picture of the effect produced upon the operation of the repulsion motor by the variation of its several constants.

Generator.

Fig. 5 lends itself readily to the tracing of the generator action of the repulsion motor.

While the machine is running at any constant speed as motor on constant-pressure circuit, connect it to a prime mover running at the same speed, then shift the brushes forward, the point B moving to the left, reaching A when $\beta = 90°$, then moving out along a similar constant-speed curve below the axis, P_1 reversing sign as B crosses the axis, $\overline{O\,C}$. Under these conditions the power output as generator is dependent upon the brush angle, β, and the speed at which the machine is driven. It is not self-exciting, but receives its exciting current from the line, although at high speeds a part of the excitation is supplied by the rotor-current.

The curves of Fig. 5 were drawn for an ideal machine without losses, and the motor and generator portions are symmetrical in consequence.

The effect of the losses is to retard the reversal of P_1 until the brush angle has attained an appreciable negative value, such that the mechanical power supplied is just equal to the losses. This effect is readily shown on the circle diagram at the expense of extreme simplicity.

[COMMUNICATED AFTER ADJOURNMENT.]

DISCUSSING PAPERS BY SLICHTER, STEINMETZ, AND OTHERS RELATING TO ALTERNATING-CURRENT RAILWAY MOTORS.

DUGALD C. JACKSON:—The writer notices that Mr. Steinmetz attributes the modern form of repulsion motor to Professor Elihu Thomson, and others including Mr. Blanck (whose discussions are stimulated by the papers of Messrs. Slichter and Steinmetz) attribute its development to Mr. Steinmetz. It seems only proper to point out that neither of these designations is historically correct. The repulsion motor capable of producing continuous rotation which was created by Professor Elihu Thomson contained an armature with individual open coils. This armature was caused to rotate by the repulsion brought to bear upon the coil which at any instant chanced to be in the most effective position,—this particular coil being short-circuited when in that position. A characteristic feature of the Thomson structure lies in the fact that the coils approach the most effective position with open circuit. When a coil reaches the effective position, it is short-circuited by the brushes and produces torque, for the short period of the short-circuit only, as the coil recedes from its most effective position.

The device which has now come to be known by the name of repulsion motor (and which is referred to in the above-named papers) is distinctly different from this. The armature winding is a closed-coil winding and the whole of the armature winding may be traversed by the induced current at every instant. This device was invented by Anthony, Jackson, and Ryan, in 1887, and the earliest published description of such a motor with which the writer is acquainted is contained in the Anthony-Jackson-Ryan patent No. 389 352 which was issued on Sept. 11, 1888. Others are said to have independently invented the same device, including William Stanley and the late Charles J. Van Depoele in this country.

This type of motor has been constructed for a number of years by the Wagner Electric Mfg. Company,—which company uses the repulsion arrangement in the starting of their single-phase induction motors. Those who have had to do with these machines have long known that the repulsion motors have characteristics which afford excellent reasons for their introduction into electric railway service when the extension of electric railway lines produces a sufficient demand for an alternating-current railway motor. When used in such service it is desirable to introduce into their construction special means for reducing or abating the sparking at the commutator which is common to alternating-current motors constructed with a commutator.

DISCUSSION AT PITTSBURG, FEBRUARY 2, 1904, ON ALTERNATING-CURRENT RAILWAY MOTORS.

V. KARAPETOFF:—The connection between ordinary direct-current series motor and the modern types of alternating-current commutator motor seems to be as follows:

First of all a neutralizing winding, N, was brought in to compensate for the armature reaction (Fig. 1). Then the idea came that in an alternating-current motor induction can be used instead of conduction. This gave two different schemes (Fig. 2 and Fig. 4), with either the armature or the neutralizing winding as secondary. In the first of these "transformer-type" motors (Fig. 2) both field coils have the same current, and can be replaced by a single coil having the resultant number of ampere-turns (Fig. 3); this is the repulsion motor. The second type (Fig. 4) can be simplified by using the armature winding itself as a neutralizing coil. To that end two auxiliary short-circuited brushes, $N\,N$, must be set at 90° to the principal brushes (Fig. 5); this is the principle used in the Winter-Eichberg and in the Latour motors.

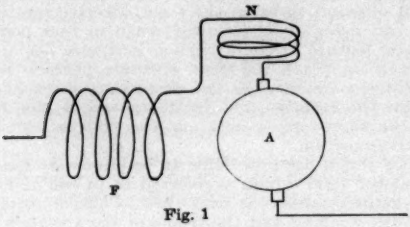


Fig. 1

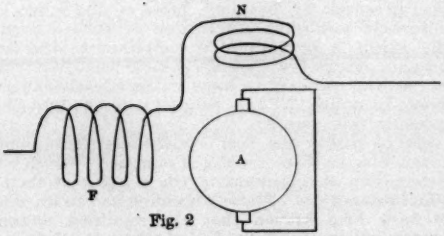


Fig. 2

The theory of the repulsion motor, as given by Mr. Steinmetz, is based upon two equations:

$$e_0 = Z\,(I + I_1 \cos w) + I\,Z_0$$

and

$$0 = -a\,x\,I \sin w + Z\,(I_1 + I \cos w) + Z_1 I_1$$

The first of these equations expresses Ohm's law applied to the primary circuit of the motor, and the second to the secondary circuit, if the e.m.f., $a\,x\,I$ sin w, induced by rotation, be considered as the applied e.m.f. of secondary circuit. All the rest of the theory simply consists in algebraical transformations of these equations to get the power-factor, the input, torque, speed, and so on.

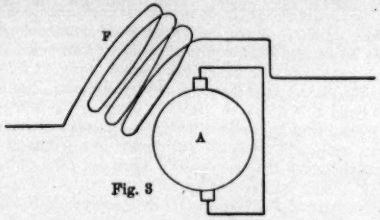


Fig. 3

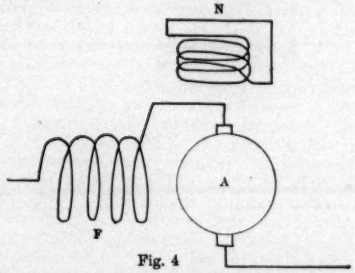


Fig. 4

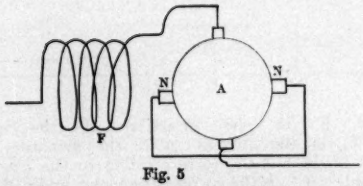


Fig. 5

An analogous equation for straight-series motor can be given (one equation, because there is but one circuit.) Let Z_m be the impedance of the field-magnet system, and Z_a the combined impedance of armature+neutralizing coil. Then with the same notations as in Mr. Steinmetz's paper

$$e_0 = a\,x\,I + I\,(Z_m + Z_a);$$

that is, the impressed voltage minus the counter e.m.f. of rotation is absorbed by the impedance of the motor.

By similar algebraical transformations, a complete theory of straight-series motor can be developed and formulas given for torque, speed, power-factor, and so on.

An excellent performance diagram of the repulsion motor was recently given by Mr. Osnos in the *Electrotechnicshe Zeitschrift*, 1903, No. 44; this diagram is shown in

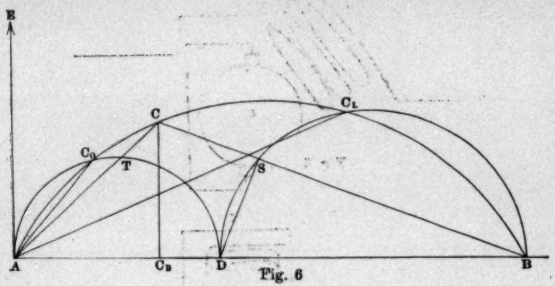


Fig. 6

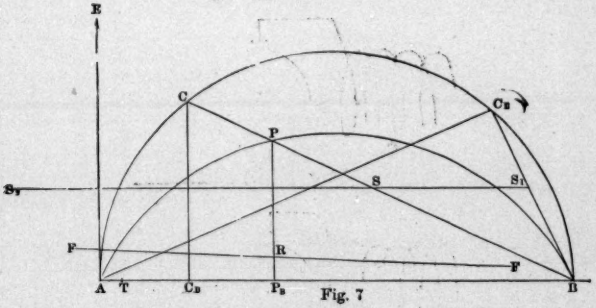


Fig. 7

Fig. 6. A E is the direction of the impressed voltage, A C_L is the current with the armature locked, drawn at an angle E A C_L, corresponding to the power-factor when so locked. A C_0 is the current at no load, and E A C_0 is the corresponding phase-angle. Draw an arc of circle, passing through C_0, C_L, and the origin A. This is the circle of input, and the angle E A C corresponds to the power-factor at any particular load. Ordinate C C_B, being the working component of the current, represents the input to the motor.

Describe the semicircle $B\,C_L\,D$, which has its centre on $A\,B$, perpendicular to $A\,E$, and passes through B and C_L. Then on $A\,D$, as a diameter, describe a second semicircle $A\,C_0\,D$. The first of these semicircles is the circle of speed and the second is the circle of torque. Thus, for a load C, the speed is represented by the ratio $\frac{C\,S}{S\,D}$, and torque by the product $C\,A \times C\,T$. Besides, $D\,C$ represents the secondary current in phase and magnitude (reduced to primary circuit.) It may easily be seen that C_L is the locked point, because for this point the segment $C\,S$ is equal to zero, hence the speed is zero.

The point C_0 corresponds to no-load run, because for this point the segment $C\,T$ is equal to zero, or torque is zero.

This diagram takes into account primary and secondary ohmic drop and primary and secondary leakage, but does not take into consideration iron loss and friction, which must either be added to the input or subtracted from the output.

A similar diagram can be developed for straight-series motor (Fig. 7), $A\,E$ and $A\,C_L$ have the same meaning as before, but $A\,C_L\,B$ circle of input is a semicircle, having its center upon $A\,B$, instead of being an arc of circle, as in Osnof diagram. Connect C_L to B and draw the arc of circle $A\,P\,B$ tangent to $C_L\,B$ and passing through A. Then draw any line parallel to $A\,B$, as $S\,S_0$. $A\,P\,B$ is the circle of output and $S_1\,S_2$ is the line of speed. For any load, as C, the vector $A\,C$ represents the current; $C\,C_2$ is proportional to the input and $P\,P_2$ to the output; the angle $E\,A\,C$ corresponds to the power-factor; abscissa $A\,C_2$ measures the torque, and segment $S\,S$ represents the speed. For C_2 (locked point) speed is equal to zero, and torque is maximum. For A (theoretical no-load) torque is zero, and speed equals infinity. The iron loss and friction can be accounted for by drawing a certain line, $F\,F$, and taking output equal to $P\,R$ instead of $P\,P_2$. The torque can also be measured from a certain point, T, instead of A, $A\,T$ representing the torque lost by iron loss and friction.

BLANK
PAGE

A paper presented at a Meeting of the Cincinnati, Branch of the American Institute of Electrical Engineers. Cincinnati, O. Feb. 15th, 1904.
Copyright, 1904. By A. I. E. E.

SINGLE-PHASE RAILWAYS.

BY W. A. BLANCK.

In perhaps no line of electrical industry has there been greater activity than in that of interurban railway construction. At the present time in the United States, particularly in the Central States, this development has reached a magnitude entirely beyond the expectations of the most sanguine of a decade since. In fact this development has gone so far that in some sections most of the best propositions are already exploited; however, there are still a great many, which, while of doubtful value with the present direct-current system—involving the use of synchronous converter sub-stations and low trolley pressure—would be very profitable if a system could be developed that would materially reduce the cost. For some time the perfecting of the single-phase motor has been suggested as the solution of this problem, since the application of this motor to electric traction means a great reduction in the cost of the transmission system. The present activity in the evolution of the single-phase railway motor gives added interest to the problem of developing and perfecting all the other details of the single-phase system.

The subjects to be considered in this paper are: 1, The fundamental characteristics of the various single-phase railway motors; 2, Certain details of line construction; and 3, The comparative cost of installing typical power-houses, sub-stations in power-houses, transmission lines, sub-stations along the road, trolley lines and feeders, and bonding of rails for a 60-mile, single-track interurban railway on direct-current and alternating-current systems.

The first problem to be solved is the development of a single-phase alternating-current motor that will operate satisfactorily

under the conditions imposed by railway service. The importance of this problem was early recognized and its solution has been sought by many of the ablest engineers both here and abroad.

The attention given the single-phase system by the technical press has brought it prominently before engineers, but a short resumé of the present state of the art may not be out of place.

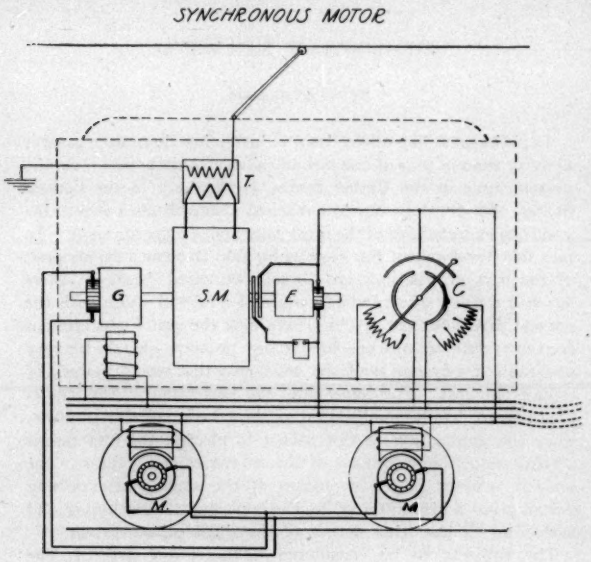


Fig. 1.

The Synchronous Motor.

The synchronous motor requires a separately-excited field, has no starting torque, and cannot be run at variable speed, therefore its direct application to railway traction is impossible. It has been proposed by Ward Leonard to use the synchronous motor in combination with a direct-current generator, to furnish direct-current to standard motors. This idea shown in Fig. 1, which is lettered to be self-explanatory.

The Induction Motor.

In respect to starting and speed-control the induction motor shows the same peculiarities as the synchronous motor; to overcome these peculiarities, Bion J. Arnold proposes a suitable combination of an induction motor with a mechanical energy-storage contrivance, this contrivance consisting of an air-compressor and tank. The various members of this combination are indicated in Fig. 2. In this system both parts of the motor are

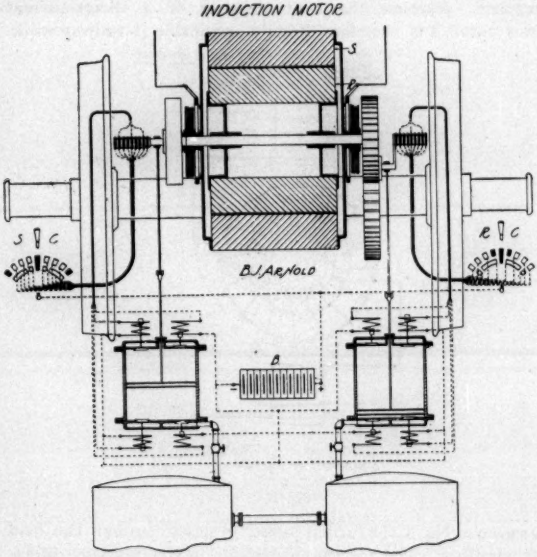


Fig. 2.

free to rotate, and they maintain a constant relative speed. The rotor is geared to the axle and also connected to one air-cylinder. The stator is connected to a second air-cylinder, in which, when the car is running at less than full speed, air is compressed. When the car is at full speed the stator is at rest and there is no compression. By admitting air to this cylinder and rotating the stator in the same direction as the rotor the car can be run at more than synchronous speed.

This combination, with the induction motor continually running, makes it possible to store energy when the car is coasting or stopped, and to use this energy when the car is accelerated. Further, this system allows the operation of the car by compressed air for a limited time, should it be desirable to run without overhead conductor.

The Series Motor.

The alternating-current series motor, as proposed by Lamme and Finzi and manufactured by the Westinghouse Electric & Mfg. Company, possesess the characteristics of a direct-current series motor; it is, therefore, directly applicable to railway work.

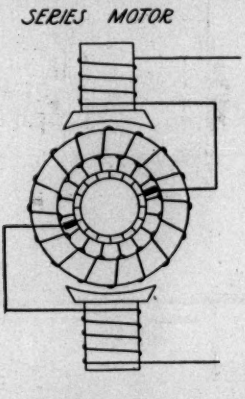


Fig. 3.

As shown in Fig. 3, the current passes in series through the field and armature. The armature is similar to the ordinary direct-current drum-type armature with commutator. As the direction of rotation in the direct-current series motor is not dependent on the direction of the current, it is evident that the motor will operate with alternating as well as with direct current.

Since the series commutator motor cannot be operated at high-pressure, it is necessary to use a step-down transformer in connection with a high-pressure trolley, thus increasing the weight of the car equipment.

The Repulsion Induction Motor.

The repulsion induction motor developed by Steinmetz and Schüler and manufactured by the General Electric Company, shows in general the same characteristics as the straight-seires motor; it can be operated directly from the high-pressure trolley, since, as indicated in Fig. 4, the armature is independent of the field. The current is induced in the armature by transformer action and can be of any desired pressure. The brushes are short-circuited and placed at an angle to give the best running conditions.

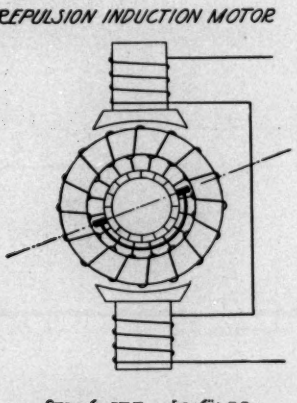


Fig. 4.

The Repulsion Series Motor.

The repulsion series motor developed by Winter-Eichberg and built by the Union Electric Company, Berlin, Germany, is similar to the repulsion induction motor with the addition of a second set of brushes, displaced 90° from the short-circuited brushes, as shown in Fig. 5. Through these brushes current is supplied by a series transformer; this is done for the purpose of decreasing the sparking at less than synchronous speed, and securing the important additional advantage of raising the power-factor nearly to unity.

Controllers.

In general, the operation of the last three motor systems is effected by master controllers operated to get the desired combinations. To obtain the voltage variation necessary for speed-control, induction regulators are used in all three cases, thus avoiding the losses consequent to the rheostatic control of the direct-current system.

Car Wiring.

To protect passengers and crew from the high pressure used in this system, it is necessary that the wiring should be done in

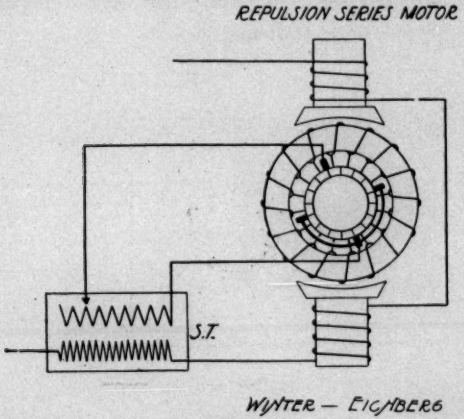


Fig. 5.

metallic conduit; this should be connected to the trucks so that any defect in the insulation of the circuit will result in the tripping of the automatic circuit-breaker in the car. Moreover, it will be necessary to insulate the steps and hand-rails to guard the passengers from shocks, which might occur during wet weather or from a car standing on a dirty rail.

Trolley Bow.

With the high-pressure working conductor it is necessary to provide against any possible short-circuiting of the trolley and its suspensions. On account of the serious results which would follow the slipping of the trolley pole so common in the present system, a suitable bow must be used instead. This trolley bow is mounted on a well-insulated platform on the roof of the car;

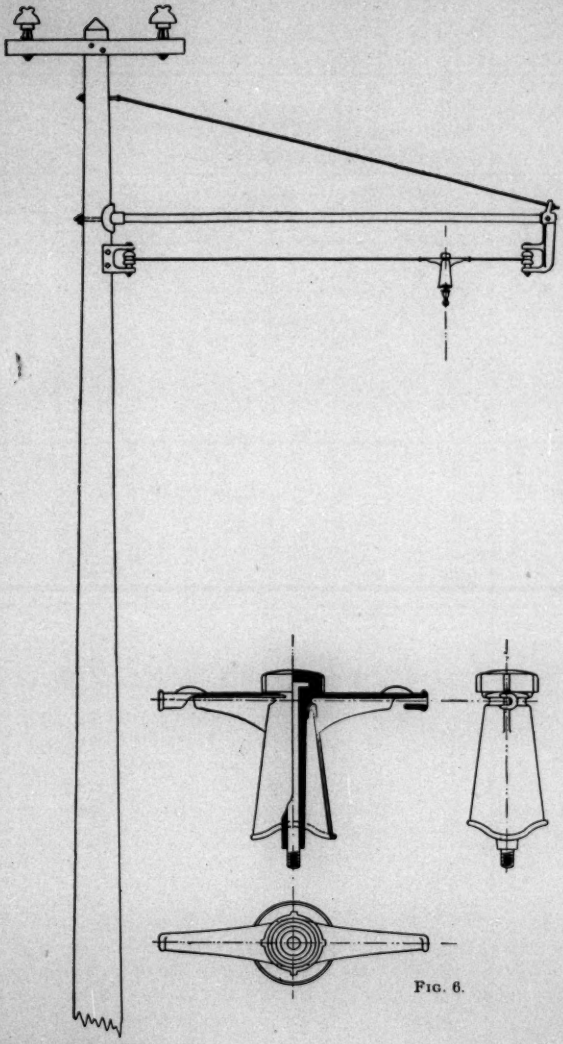


FIG. 6.

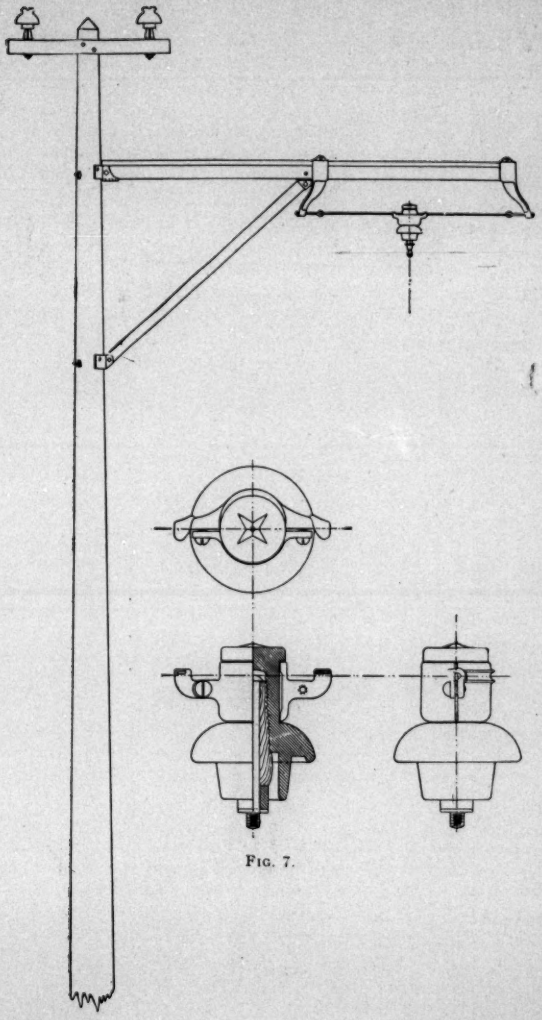


FIG. 7.

this platform also supports the springs necessary to maintain the requisite pressure between the bow and the trolley wire. A small air-cylinder, mounted on the same platform, operated by compressed air from the brake system, should be so connected as to lay the bow flat on the roof of the car, in case the necessity arises to disconnect temporarily the bow from the trolley. The contact part of the bow can be made either of soft copper or aluminum. The necessary lubrication is accomplished by grease applied in a slot extending the length of the bow. The bow should be of such length that no manipulating will be necessary when reversing the car.

The trolley bow in use on the Valtelina road in Northern Italy with a working pressure of 3000 volts, consists of copper cylinders rolling in insulated ball-bearings. Brushes take the current from these revolving cylinders to the steel tubes carrying the contact-piece.

Trolley-Line Construction.

In order to protect life and property, great care must be used in constructing the high-pressure trolley line. There is a prevailing idea that high-pressure trolleys are dangerous, and it is said that this condition will retard the development of alternating-current railways operated over public property; but there is no reason why these trolleys should not be made as safe as the high-pressure distributing systems of lighting companies, now so common on public property.

It is important to provide a hanger that will readily withstand the working pressure of the system, and one that can be easily replaced in case of mechanical or electrical defects. Fig. 6 shows a trolley-line construction with hangers similar to that used on the Valtelina railway. The bolt carrying the trolley-clamp is surrounded by an insulating compound, called ambroine, and set into a malleable iron bell provided with clamp-arms to secure it to the span-wire. A cast-iron cap-screw holds the insulated bolt firmly in place.

Another construction used on the Lansing, St. Johns & St. Louis Railway, in Michigan, is shown in Fig. 7. The hanger consists of a special high-pressure glass insulator fastened to the span wire in the usual way. The working conductor is carried by an iron pin inserted in a wooden sleeve, on which is turned a thread to fit the glass of the insulator. A thin lead bushing allows the insulator to be firmly clamped by the malleable-iron supports, thus preventing the hanger from jarring loose.

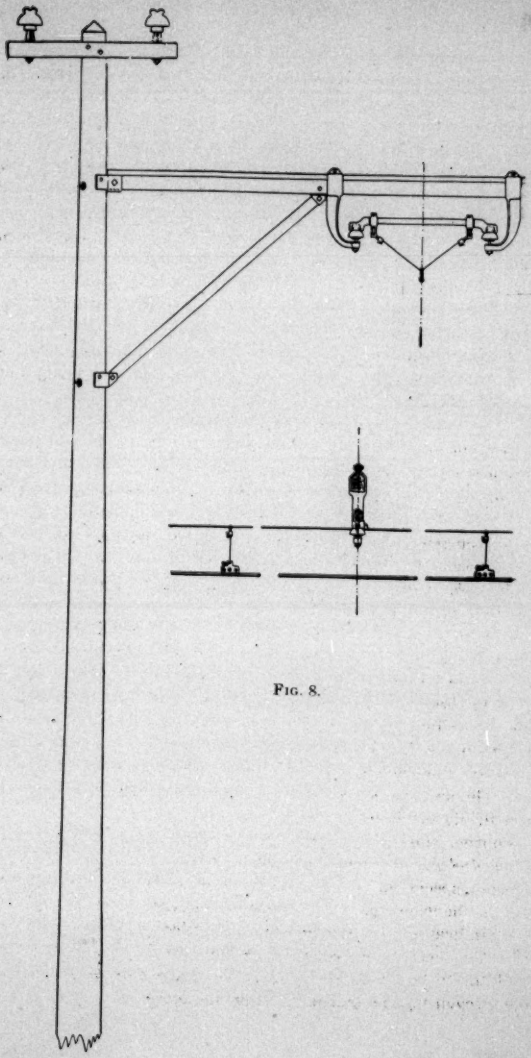
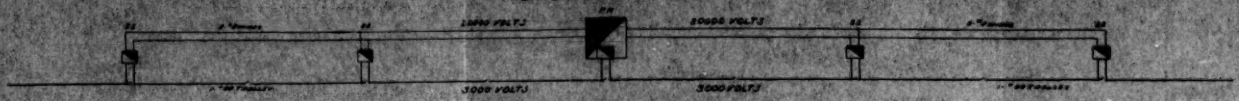
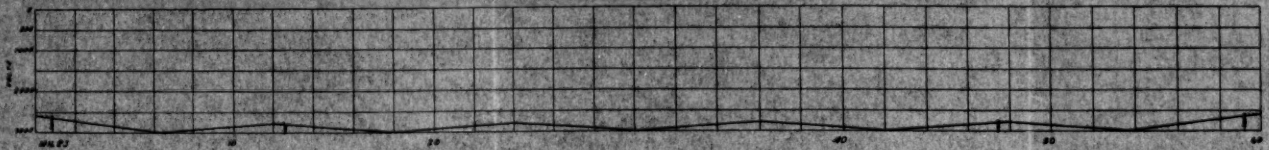


FIG. 8.

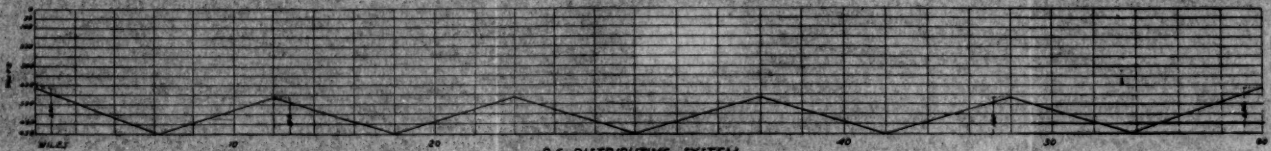
A.C. DISTRIBUTING SYSTEM



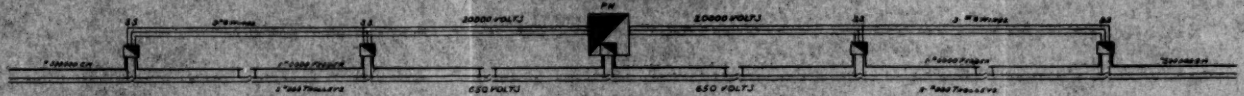
A.C. LINE DROP FOR 300 K.W. WITH 80% POWER FACTOR



D.C. LINE DROP FOR 300 K.W.

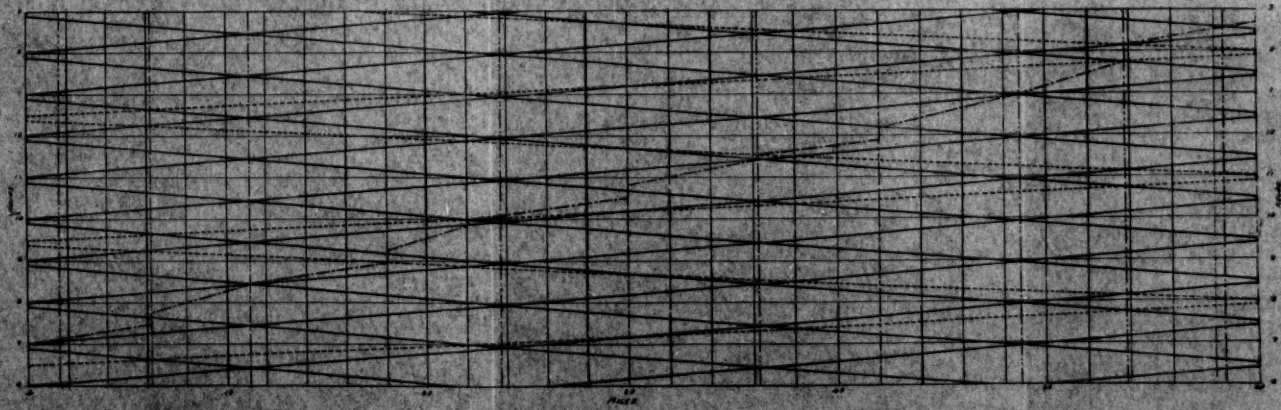


D.C. DISTRIBUTING SYSTEM



SCHEDULE

Local Cars ——— Express Cars - - - - - Freight and Baggage Car - · - · -



If the road operates on a public highway, special precautions should be taken to avoid accident. One solution is shown in Fig. 8; in this the working conductor is suspended at intervals of about ten feet from two steel wires. In case of a mechanical break in the trolley wire it is evident that the end cannot reach the ground or injure passers-by. It might be noted in passing that this construction increases the carrying capacity of the trolley with but slightly greater investment. A construction somewhat similar to this is in use on the single-phase railway near Berlin.

In regard to returning current through the rails, it may be said that with the proposed frequency of 25 cycles per second and the small current required with the higher pressure, this loss will be even smaller than in direct-current railway work, so that for normal interurban service it will be sufficient to bond only one rail. This has the advantage, greatly to be desired in many cases, of leaving the other rail free for the purpose of block signals. Furthermore, the evils of electrolysis are completely avoided with the alternating-current system.

In order to consider more in detail the relative merits of the alternating-current and direct-current systems of distribution, parallel computations and diagrams may be made for the case of a 60-mile, single track, interurban road. We shall assume the power-house to be located at the centre of the line and to contain one sub-station, and that four sub-stations are located at equal intervals on the line, as shown in Fig. 9. Although the alternating-current system will not require sub-stations at as frequent intervals as in the direct-current system, they are retained on account of the advantage derived from sectionalizing the line, and the better distribution of power due to the larger number of feeding points.

The schedule proposed requires five local cars having one-hour headway; one express-car, making the round trip in three hours, and one freight- and baggage-car making the trip between the two terminals in about eight hours.

The average power required by the various cars in kilowatts will be as follows:

	Weight in tons.	Schedule speed in miles per hour.	Watt-hours per ton-mile.	Kilowatt-hours per trip.	Average power in kilowatts
Local-car.....	30	25	80	144	60
Express-car.....	35	42.8	110	231	165
Freight-car.....	30	12	70	126	25

With the schedule outlined above, the average load on all five sub-stations will be about 500 kw., or 100 kw. per sub-station, while the maximum load per sub-station under certain conditions

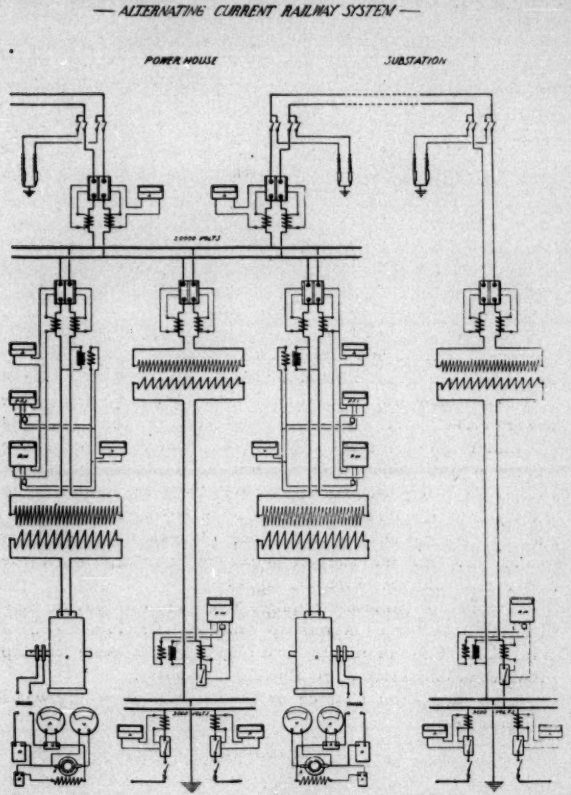


FIG. 9.

is 450 kw., for instance, when the express-car is starting and two locals are running in one section. With a proper momentary overload allowance this assumed condition will require one

300-kw. synchronous converter per sub-station in the direct-current system. In the alternating-current system, however, a static transformer of 200-kw. capacity per sub-station will be ample. The maximum load at the power-house will be 800 kw. and two 400-kw. units will suffice, if for the purpose of this comparative study no reserve capacity be provided either in power-house or sub-stations.

Some idea of the relative simplicity of the transmission systems in the two cases may be obtained from a consideration of the accompanying wiring diagram, Fig. 10, showing the apparatus and connections required in each case. In both cases step-up transformers raise the total generator output to the high transmission pressure, and a step-down transformer set is placed in the power-house. Although the power-house sub-station could take its supply directly from the generators, it is preferred to use one general form for all sub-stations, thus avoiding special switching arrangements. For the three-phase transmission lines of the direct-current railway system, three No. 6 wires are assumed, and for the single-phase transmission line two No. 4 wires, costing respectively $10 000 and $11 500.

The proportions of the distributing-system have been calculated for the following conditions: for the direct-current system it is assumed that the maximum drop in line pressure in the case of a car starting at its maximum distance from sub-stations is approximately 200 volts, or about 30%. This condition can be obtained by installing two No. 000 trolley wires and No. 0000 feeder capacity between sub-stations, and 500 000 circular mils feeder for the stub-ends. The cost of the copper under these conditions will be about $95 000.

For the alternating-current system the size of the trolley wire has been determined from mechanical rather than from electrical considerations. A No. 00 grooved trolley wire has been assumed installed throughout the length of the line, since for this class of service it is not practicable to use smaller sizes. The cost of the copper in this case will be $21 500.

In determining the drop for this system, 80% power-factor is assumed. It will be noted that the maximum drop under the same conditions as above mentioned will be 190 volts between sub-station, or 6.25%, and 380 volts on stub ends, or 12.5%. This shows a considerable advantage in favor of the alternating-current system.

At present the alternating-current motor weighs somewhat

more than the direct-current motor, and operates at a slightly lower efficiency. However, the smaller efficiency of the alternating-current motor is more than counterbalanced by the small

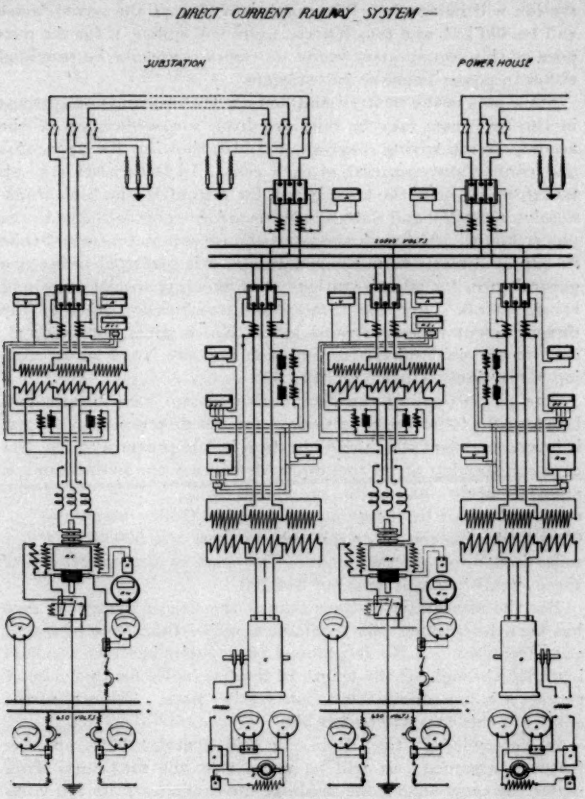


FIG. 10.

percentage loss in the alternating-current distributing system. And, furthermore, with the rapid development now taking place in the alternating-current motor, it is safe to assume that in the

very near future its characteristics as to weight and efficiency will soon equal those of the direct-current motor, thus making the advantage of the alternating-current railway system still more evident.

An idea of the relative first cost for the two systems may be obtained by arranging in parallel columns the cost of the various items; this is done in the accompanying table and diagram. It is not necessary to take up in detail all the items, as they speak for themselves, but it may be of interest to note some items in which the costs vary more widely:

The single-phase generators, as would be expected, cost nearly 30% more than three-phase generators, this increase in cost amounts to $5000. Small savings on switchboard and wiring reduce the total for the power-house $3500 in favor of the direct-current system.

For the sub-station in the power-house, principally on account of saving in converter and transformer capacity, the balance is $8000 in favor of the alternating-current system.

The transmission systems are approximately the same, there being $2000 in favor of the alternating-current system.

In the alternating-current distributing system, while the suspension of the trolley is noticeably more expensive than in the direct-current system, on account of special insulators, the immense saving in copper gives a balance of $78 000 in favor of the alternating-current system.

The necessity of bonding only one rail effects a saving of $16 000, in favor of the alternating-current system.

A very liberal allowance has been made by placing the cost of the alternating-current motor equipments one third in excess of that of the direct-current motor equipments; this, as above noted, is the present cost of the alternating-current equipment, and without doubt in the near future this difference will be greatly reduced.

The total investment for the direct-current system under the assumed conditions is $490 100, while that of the alternating-current system is $371 600. Reducing this to the cost per mile, it is found that the electrical equipment complete amounts to $8168 for the direct-current system, and $6193 for the alternating-current system, or a saving of $1955 per mile in favor of the alternating-current system. Expressed in percentage, this means that the alternating-current system effects a saving of 25% of the cost of the direct-current system; in

other words, the cost of the direct-current system is 32% more than the cost of the alternating-current system, a showing

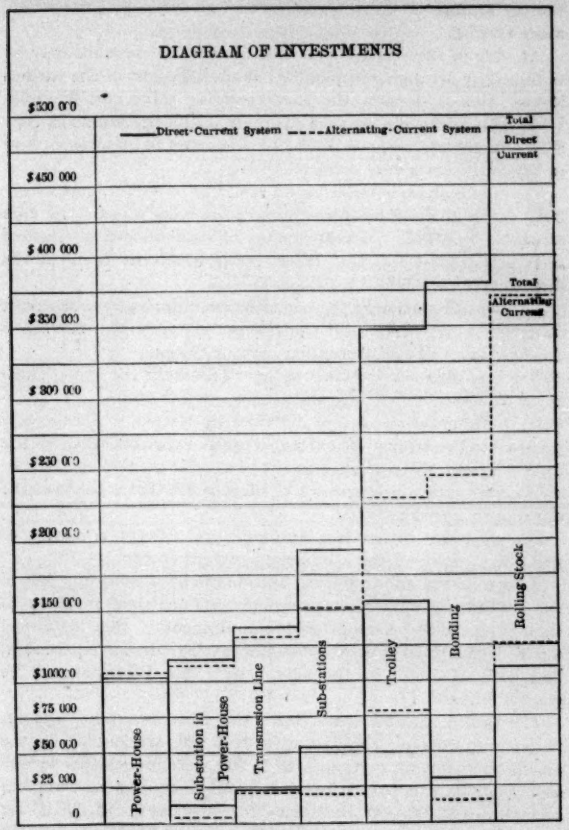


FIG. 11.

most favorable for the latter, and this indeed during the first year that this apparatus has been on the market.

With the alternating-current motor thus far perfected and

the large number of propositions whose realization is conditioned by a cheaper electrical equipment, it looks as if the alternating-current system would be very widely adopted.

ESTIMATED COST OF THE ELECTRICAL EQUIPMENT OF A 60-MILE, SINGLE-TRACK INTERURBAN RAILWAY.

POWER-HOUSE.	*Direct-Current System.*	*Alternating-Current System.*
Building	$10 000	$10 000
Foundations	2 500	2 500
Boilers and settings	12 000	12 000
Steam piping and covering	7 500	7 500
Engines	22 000	22 000
Generators: two 400-kw.	18 000	23 000
Exciters	1 000	1 000
Step-up transformers, 800-kw.	8 000	7 500
Switchboard	3 500	3 000
Wiring	3 000	2 500
Feed-water heater	800	800
Pumps	800	800
Coal storage	1 000	1 000
Smoke-stack and flues	2 000	2 000
Fuel economizers	3 000	3 000
Stokers	3 500	3 500
Incidentals	4 400	4 400
Totals	$103 000	$106 500

SUB-STATION IN POWER-HOUSE.	*Direct-Current.*	*Alternating-Current.*
Building extension	$1 000	$600
Synchronous converter, 300-kw.	4 800	
Transformer, 300-kw.; 200-kw. alternating current	3 200	2 000
Switchboard	2 000	1 300
Wiring	1 000	500
Incidentals	600	200
Total	$12 600	$4 600

48-MILE TRANSMISSION LINE.	*Direct-Current.*	*Alternating-Current.*
Poles charged to trolley line		
Copper	$10 000	$11 500
Insulators, pins and cross-arms	7 500	5 000
Erection	4 000	3 000
Incidentals	1 000	1 000
Total	$22 500	$20 500

SUB-STATION ALONG THE ROAD.	*Direct-Current.*	*Alternating-Current.*
Building	$2 000	$1 000
Synchronous converter	4 800	
Step-down transformers	3 200	2 000
Switchboard	2 000	1 300
Wiring	1 000	500
Incidentals	500	200
Total	$13 500	$5 000
Four sub-stations	$54 000	$20 000

TROLLEY-LINE AND FEEDERS	*Direct-Current System.*	*Alternating-Current System.*
Poles, 3500	$17 500	$17 500
Poles distributed and set	4 000	4 000
Guys and anchors	2 000	2 000
Brackets with hangers	18 000	25 000
Copper, direct current:		
Feeder 12 miles, 500 000 cir. mils		
" 48 " No. 0000		
Trolley, 120 " No. 000	95 000	
Alternating current:		
Trolley, 60 miles, No. 00		21 500
Feeder insulators	2 000	
Erection	10 000	4 000
Incidentals	7 500	4 000
Total	$156 000	$78 000

BONDING OF RAILS.	*Direct-Current.*	*Alternating-Current.*
Both rails bonded	$30 000	
One rail bonded		$15 000
Cross bonds	2 000	1 000
Total	$32 000	$16 000

ROLLING STOCK.	*Direct-Current.*	*Alternating-Current.*
10 vestibuled passenger-cars, each equipped with 4 motors, and weighing about 30 tons	$75 000	$85 000
2 express passenger-cars, equipped with 4 motors and weighing about 35 tons	18 000	20 500
2 Baggage-cars, each equipped with 4 motors and weighing about 30 tons	10 000	12 000
Snow-plow and construction-car	7 000	8 500
Total	$110 000	$126 000

RECAPITULATION.	*Direct-Current.*	*Alternating-Current.*
Power-house	$103 000	$106 500
Sub-station in power-house	12 600	4 600
Transmission line	22 500	20 500
Sub-stations	54 000	20 000
Trolley-line and feeders	156 000	78 000
Bonding	32 000	16 000
Rolling stock	110 000	126 000
Total	$490 100	$371 600

Cost per mile, direct-current system..... $490 100/60 = $8 168
" " alternating-current system.... 371 600/60 = 6 193

Saving per mile, alternating-current system.... $1 955

The decrease of alternating-current cost in terms of direct-current investment, 25%.

The increase of direct-current cost in terms of alternating-current investment, 32%.

A paper presented at the 184th Meeting of the American Institute of Electrical Engineers, New York, Feb. 26th, 1904.
Copyright 1904, by A. I. E. E.

THE CONDUCTIVITY OF THE ATMOSPHERE AT HIGH VOLTAGES.

BY HARRIS J. RYAN.

SYNOPSIS.

The present paper gives an analysis of the factors that are responsible for the nature of the atmospheric loss occurring on high-voltage lines as reported by Mr. Charles F. Scott in his paper that was published in the A.I.E.E. TRANSACTIONS, Vol. XV., p. 531, 1898, based upon results obtained by himself and those obtained by Mr. Ralph D. Mershon. The analysis shows that the equation

$$E_{max} = 2055 \log_{10}\left(\frac{s}{r}\right) D' (r+d) \times 10^{10} \qquad (10)$$

expresses the relation between the voltage, conductor sizes, and separation at which the sudden rise occurs in the curve of " loss between wires " at ordinary barometric pressures and temperatures wherein

E_{max} = the maximum value of the voltage-wave applied to the line.

r = the radius of the line conductor in inches.

s = the separation of the line conductors from center to center in inches.

d = the distance from the conductor surface at which the strain due to the electrostatic field causes initial atmospheric rupture.

D' = the strength of the electrostatic field of force (*dielectric flux-density*) that will electrically rupture the atmosphere at the distance d from the surface of the conductor having a radius r measured in coulombs per square inch.

To this is added an account of the experiments that were made to determine the above values of d and D' in relation to r and the effects due to barometric pressure and temperature changes and to the presence of moisture.

The values found for d and D' in relation to r at a barometric pressure of 29.5 inches of mercury and a temperature of 70° fahr. are given in the following table:

B. & S. G.	$2r$.	d.	D'.
20	0.03196	0.0050	350×10^{-10}
15	0.05706	0.0100	300×10^{-10}
10	0.10189	0.0180	275×10^{-10}
8	0.12849	0.0220	258×10^{-10}
6	0.16202	0.0350	200×10^{-10}
4	0.20431	0.0700	171×10^{-10}
2	0.25763	0.0700	170×10^{-10}
Measurements upon conductors of larger sizes to the limit of a diameter of 0.625 inch.	0.625	0.0700	170×10^{-10}

The experiments demonstrated that the voltage at which the atmospheric line loss is inaugurated varies as the atmospheric density; *i.e.*, directly as the barometric pressure and inversely as the absolute temperature. On substitution of corresponding values obtained by experiment, equation (10) takes the following practical form:

$$E_{max} = \frac{17.94b}{459.+t} \times 2055 \log_{10}\left(\frac{s}{r}\right) D'(r+d) \times 10^{10} \qquad (12)$$

wherein

b = the barometric pressure in inches of mercury.

t = the temperature in degrees Fahrenheit.

Since the values of d and D' are constant for diameters of conductors larger than 0.250 *inch*, it follows that equation (12) for corresponding conductors reduces to

$$E_{max} = \frac{17.94\, b}{459 + t} \times 350\,000 \log_{10}\left(\frac{s}{r}\right)(r + .07) \qquad (13)$$

The results obtained by calculation employing equations (12) and (13) are compared with the measurements made by Mershon on the Telluride high-altitude line in 1898 and those obtained by Professor Harold B. Smith upon the Worcester Polytechnic Institute laboratory line in 1901 and 1902 at ordinary altitudes.

Efforts were made to determine the effects of the presence of moisture upon the point at which the atmosphere about high-voltage lines becomes conductive, *i.e.*, upon the point at which the sudden rise in the loss-curve occurs. However, no definite effect of this sort could be found, and this is practically in accord with Mershon's conclusions after his observations made upon the Telluride line under variable weather conditions. If there is such an effect it must be small.

The following table of values has been calculated by means of equations (12) and (13). It shows the corresponding diameters of line conductors that must be employed to avoid loss between wires for a series of line voltages wherein the barometric pressure is 29.5 inches of mercury, the temperature 70° fahr., and the distance between the conductors 48 inches.

Maximum volts at which atmospheric conduction loss occurs.	Corresponding effective volts (sine wave)	Operating pressure, 90 per cent of corresponding effective volts.	Diameters of conductors in inches.
78 500	55 000	50 000	0.058
118 000	83 300	75 000	0.106
157 000	111 100	100 000	0.192
235 500	166 600	150 000	0.430
314 000	222 200	200 000	0.710
392 000	277 700	250 000	0.990

The real voltage limit to-day in transmission is due to the insulator, where the line has to be exposed to the weather. In the future the insulator difficulty will be solved in one way or another and higher voltages will be used. Possibly in large undertakings the line may be protected from the elements by means of a con-

tinuous covering. It is evident that when such high voltages are employed atmospheric conduction, or "the brush" (as one experienced high-voltage engineer termed it in conversation with the writer), must be avoided. High voltage brush discharge was studied and reported upon in the A.I.E.E. TRANSACTIONS by Dr. Steinmetz.* He applied to it the term *corona*. The present paper shows that the brush discharge or corona occurs always when a definite strain exists in the atmosphere next to the high-voltage conductors, and that to avoid such corona with its destructiveness and waste of power it is necessary on transmission lines and auxiliaries to proportion things so as to keep the dielectric strain of the atmosphere below a definite point above which the corona will inevitably develop.

In the above table a factor of safety of 1.11 or a margin of 10 per cent has been allowed in estimating the safe voltage at which to operate so as to avoid losses due to brush discharge. This is a laboratory conclusion only. In application the following points must be kept in mind:

1. Without special care there will be doubt in advance as to the exact value that the voltage wave will not exceed. Almost invariably the line-charging current will cause important line-voltage wave-distortion so that the maximum of the wave will exceed the effective value of the voltage by a factor much greater than the *square root of two*. The corona formation depends primarily upon the maximum and not upon the effective value of the wave; this has been found by Scott, Mershon and others, as well as in the present experiments.

2. One must remember that unless the insulators are properly proportioned, after the cross-arms and pins have been exposed to the weather for some time and have become conductive, the presence of the insulators made of material that has a considerably greater permeability to dielectric flux (greater specific inductive capacity) than the atmosphere, will cause corona to a greater or less degree to form over the conductors in their neighborhood, even if the line has been proportioned so as to avoid corona or atmospheric conduction over the remaining portion of the conductors. The presence of corona upon the conductors in the neighborhood of the insulators will likely be accompanied by corona over the pins inside the insulators, resulting in their

*TRANSACTIONS A.I.E.E., Vol. X, p. 85, 1893.

ultimate injury if made of wood from this cause alone, even if the surface leakage current is so limited as not to injure the pin.*

In view of the above it is evident that practical experience and not the laboratory must eventually determine the factor of safety that should be allowed under given circumstances in lieu of the 1.11 factor or the 10 per cent margin allowed in the above table.

The paper closes with the suggestion that when viewed in the dark the corona formed upon wires of given diameters and distances apart provides a method for gauging high voltages that is free from the short-circuit and surging disturbances occasioned by the use of the spark-discharge method. Either two parallel conductors or a conductor mounted at the center of a cylinder may be employed for this purpose.

Former Studies of Atmospheric Conduction.

The atmosphere is ordinarily the general medium in which electric circuits and apparatus are immersed. It is depended upon to a greater extent for insulation than any other medium or material.

Its dielectric strength to resist disruption by electric forces, in bulk, under ordinary conditions as to temperature, barometric pressure and entrained moisture, from an engineering point of view, has been the subject of extensive and critical investigation by Steinmetz, whose results have been communicated to the Institute in several papers.

Steinmetz found in his studies of the electric disruptive strength of the powerful solid dielectrics that the atmosphere surrounding the solid dielectric specimen and the electrodes applied thereto would break under the strain formed by the flux of electric force through it, much more readily than the solid dielectric. This gives rise to envelopes of conductive atmosphere located around the electrodes and over the surfaces of the powerful dielectrics. This phenomenon, which has the appearance of the familiar brush discharges so easily obtainable in electrostatic experiments was studied at some length and he applied to it the term *corona*.

Scott subsequently investigated experimentally the conditions under which the atmosphere in close proximity to high-voltage lines is subjected to electric stresses that bring it to the breaking point, causing the formation of brush discharges accompanied by losses of power in measurable amounts. Mershon,

*Burning of Wooden Pins on High-Tension Transmission Lines by C. C. Chesney, Transactions A.I.E.E., Vol. XX., p 435, March 22, 1903.

independently of Scott, carried out a series of experiments at Telluride, Colorado, in which losses between wires due to high voltage were measured on a line 2.25 miles long, whereon the conductors having a diameter of 0.162 inch were mounted at various distances apart and between which pressures varying from 20 000 to 60 000 volts were applied. The results obtained through this series of investigations by Mershon and by Scott and his co-workers were reported by Scott to the INSTITUTE in a paper at the June meeting in 1898.

The characteristic phenomena of greatest interest to the engineer, as brought out in this classic paper, are those to which the Telluride curves of voltage and line-loss apply and which are charted in Fig. 6, Vol. XV., p. 545, as determined by Mershon and which for convenience is reproduced as Fig. 1 of the present paper.

The experimental and analytical study upon which this paper is based was undertaken for the purpose of securing further knowledge of the nature of the line-loss as observed by the above gentlemen.

THE ELECTROSTATIC FIELD.

When the terminal faces of a dielectric are in contact with conductors between which an electromotive force is applied, an electric force is exerted throughout the dielectric in variable degree, according to the position with reference to conductors. This electric force produces a distortion of the atomic structure of the dielectric; *i.e.*, a displacement of the electrons forming the dielectric atoms. Such electron-displacement, while in progress, constitutes an electric current. The displacement encounters the reaction due to internal atomic forces which tend to maintain the original structural form. This reaction is the cause of the formation of the familiar counter electromotive force of a condenser and is in proportion to the total amount of electricity or the time-integral of the current that was passed through the dielectric. When the process of atomic distortion proceeds beyond the point of structural rupture, the ordinary conduction-current ensues. Thus through a dielectric prior to the rupturing point the only current that can be passed is a *displacement current*. The passage of such displacement current and the establishment of the corresponding field of electrostatic force are merely cause and effect in one and the same operation. In any portion of the dielectric the value of the strength of the electrostatic field of force therein established is proportional to the

displacement of electricity, *i.e.*, to the time-integral of the displacement current that accompanied the establishment of such electrostatic field. For engineering purposes, therefore, the time-integral of displacement current may be conveniently employed as a measure of the strength of the corresponding electrostatic field of force.

The energy that is taken up in the formation of an electrostatic field of force per unit dielectric volume and which has been applied, therefore, in the passage of the corresponding time-integral of displacement current, is

$$J = \tfrac{1}{2} C E^2 \qquad (1)$$

where C is the capacity in farads; *i.e.*, the coulombs of displacement current per volt.

When an electromotive force of *one volt* is applied to the opposite faces of a centimetre-cube of air at ordinary barometric pressure and temperature, the energy taken up by the electrostatic field formed thereby throughout the cube, will be

$$441.7 \times 10^{-10} \text{ joules}$$

No important change in this value occurs with variation of barometric pressure and temperature. When it is substituted in equation (1) the corresponding strength of electrostatic field thus produced per volt per centimetre of air expressed in coulombs of displacement current per square centimetre is found to be

$$C = 883.4 \times 10^{-10} \qquad (2)$$

For present convenience *strength of electrostatic field of force* will be referred to as *density of dielectric flux*. It may, therefore, be stated with reference to the dielectric permeability of air that,

One volt applied through a distance of one centimetre in air will establish a dielectric flux density of 883.4×10^{-10} *coulombs per square centimetre.*

This is the same thing as the capacity in farads of a condenser having surfaced electrodes of one square centimetre each, facing opposite sides of a centimetre cube of air.

In this method of designation it follows that the density of dielectric flux established per volt per unit area of conductor-terminal face is equal to the capacity in farads per unit area of such face. Thus in connection with a transmission line the total dielectric flux set up between conductors per unit length will be the product of the capacity of such unit length of line in farads and the applied electromotive force. The corresponding

density of dielectric flux extending from the surface of either conductor is the total flux per unit length divided by the corresponding conductor surface.

ANALYTICAL STUDY OF MERSHON'S RESULTS.

From the work of Steinmetz it is known that

a. The atmosphere and the gases generally, conduct after disruption in two forms:

1. Arcs or very hot streamers. A concentrated conduction at high current-density.

2. Corona or brush discharge. A diffused conduction at low current-density, developing heat at lower intensity.

b. 1. The dielectric strength of the atmosphere in bulk is such as to require for rupture approximately a pressure-gradient of 10 000 sine wave effective volts per inch.

2. The thin zones of atmosphere that enclose the electrode and which are in immediate contact therewith have a far greater dielectric strength than air in bulk, corresponding to a ratio of dielectric strengths of from five to ten.

From the nature of sparking discharges through air the conclusion is reasonable that whenever the flux of electric force, or more briefly the dielectric flux, through the air in a given state as to temperature, pressure, and freedom from foreign material, rises to a certain value an atomic structural rupture of the air will occur, resulting in conduction.

From Steinmetz's results it is evident that this maximum value of dielectric flux-density at which atmospheric disruption will not occur will depend upon the position of the particular portion of the atmosphere being considered relative to the conductors or electrodes between which the high voltage is applied.

The classic electrostatic experiments as well as the modern Paschen's law,* which has been tested to above five atmospheres and which asserts that the sparking discharge voltage through given distances in air increases with the atmospheric density and, therefore, as the pressure and inversely as the temperature on the absolute scale, make it reasonable to conclude that the minimum dielectric flux density that will cause atmospheric conduction will vary as the atmospheric density and therefore directly as the barometric pressure and inversely as the temperature on the absolute scale.

*Conductivity of Electricity through Gases. J. J Thomson, Edition of 1903, p. 367.

The researches of Hittorf, Crooks, J. J. Thomson and others, including some recent work upon this particular point by Dr. Blaker, make it reasonable to conclude that so far as concerns magnitudes which are appreciable in engineering, the atmosphere under ordinary conditions and fairly clean, *i.e.*, free from floating

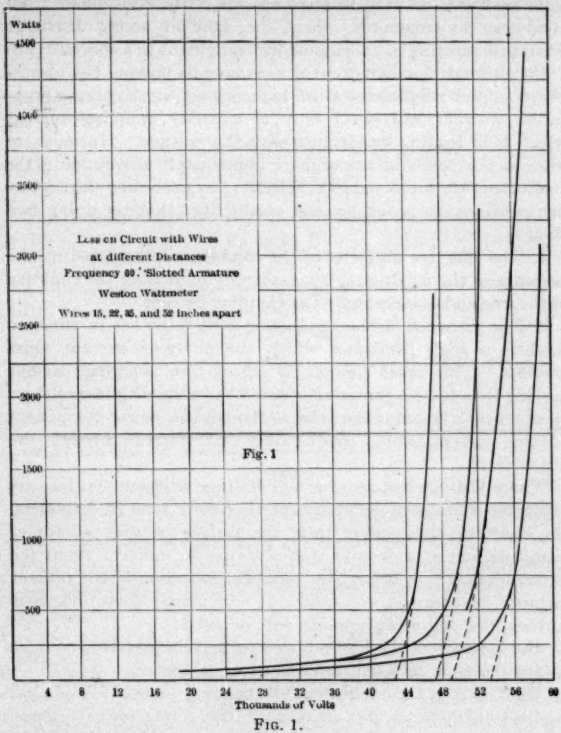


FIG. 1.

conducting material, will not conduct appreciably in the neighborhood of high voltage lines when their surfaces are bare, so long as no portion of such atmosphere is permeated with a dielectric flux that is not sufficient to cause rupture at any one point.

When the dielectric flux exceeds the rupturing point, conductivity ensues and there is a conductive transfer of current from conductor to conductor through the atmosphere.

On continuous-current circuits the amount of transfer of such current must be small prior to the application of a voltage sufficient to break entirely through the dielectric atmosphere from conductor to conductor, when the familiar arcing discharge occurs, amounting in an engineering equipment to a short-circuit.

On alternating-current circuits, as long as none of the atmosphere in the neighborhood of high-voltage conductors is ruptured, transfer will occur only of capacity charging current which is in leading quadrature with the voltage. However, as soon as the zones of atmosphere immediately surrounding the conductors are subjected to a dielectric flux exceeding the rupturing point, such zones become conductive, thereby doing two things:

1. The effective diameter of the conductor is increased by the presence of the conducting zone, thereby increasing the capacity of the line and consequently the charging current.

2. The presence of the conducting zone must act in effect to produce a high resistance which the charging current must traverse. This must produce a lag in the charging current causing it to have a power-component in phase with the voltage. In effect such action is the same as though the power-component of the current were conductively transferred through the atmosphere.

Where the conductors of a high-voltage transmission line are separated a distance between centers of more than 20 diameters, the dielectric flux passes from the surface of a conductor of round section at a density that is so nearly uniform about the circumference that it may for practical purposes, in the present instance, be assumed constant. In discussing these relations further the following symbols will be used:

C, the capacity of the line in farads per inch of length.

s, the distance between the conductors in inches.

r, the radius of the conductors in inches.

ϕ_0, the total dielectric flux established from conductor to conductor, measured in terms of the corresponding displacement current; *i.e.*, in coulombs.

D_o, the dielectric flux-density at the surface of the conductor in coulombs per square inch of sectional area.

D', the corresponding dielectric flux-density at a distance slightly remote from the surface of the conductor, where the

extraordinary dielectric strength of the atmospheric zone ceases and where occurs the region of greatest dielectric strain relative to the disruptive strength.

D, the corresponding dielectric flux density at any point.

The capacity between wires in farads per inch of line is

$$C = \frac{0.00306}{\log_{10}\left(\frac{s}{r}\right)} \times 10^{-10} \quad (3)$$

The total displacement current and, therefore, the total dielectric flux established between conductors per inch of line at the line voltage, E, is

$$\phi_0 = EC = \frac{0.00306}{\log_{10}\left(\frac{s}{r}\right)} \times E \times 10^{-10} \quad (4)$$

The dielectric flux density at the surface of the conductor is

$$D_0 = \frac{\phi_0}{2\pi r} \quad (5)$$

$$D_0 = \frac{0.00306}{2\pi r \log_{10}\left(\frac{s}{r}\right)} \times E \times 10^{-10} \quad (6)$$

At a radial distance d from the surface of the conductor, the corresponding dielectric flux density is

$$D' = \frac{\phi_0}{2\pi (r+d)} \quad (7)$$

$$D' = \frac{0.00306}{2\pi (r+d) \log_{10}\left(\frac{s}{r}\right)} \times E \times 10^{-10} \quad (8)$$

In alternating-current work the maximum values of D_0 and D' are wanted, and the maximum values of the voltage waves must, therefore, be used for E; as reduced from equations (7) and (8), thus:

$$E_{max} = 2055 \log_{10}\left(\frac{s}{r}\right) . r . D_0 \times 10^{-10} \quad (9)$$

$$E_{max} = 2055 \log_{10}\left(\frac{s}{r}\right) (+d) D' \times 10^{-10} \quad (10)$$

When Mershon's results given in Fig. 1 were used to test these equations it was found that they correctly accounted for the relation between the separation of the conductors and the voltage at which the initial brush discharge took place. These results gave also a certain value for D_0 which would not give correct

*Perrine and Baum, TRANS., A. I. E. E., Vol. XVII., p. 332, May 18, 1900.

results when used to determine the voltage required to start the line loss for the small wires used by Scott in some of his experiments at Pittsburg.

At this point a rough laboratory test was made to see whether one would find the start of the loss between wires to occur at the same voltages for the same size of conductor and distances apart

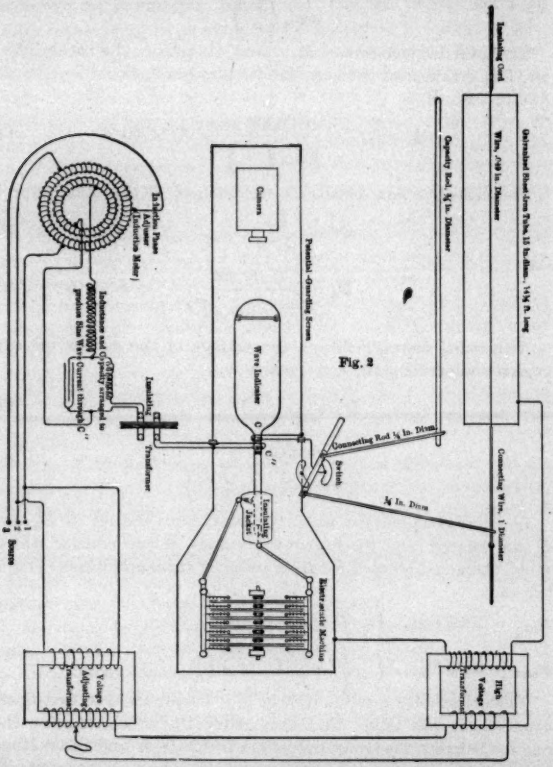


FIG. 2.

that Mershon found. The results obtained were totally different. It became evident from this disagreement that barometric and

temperature variations exerted important influences. The difference between the approximate results obtained by the author and those of Mershon indicated that the voltage starting the loss between wires would vary as the barometric pressure. When, however, the values deduced from the Telluride results were correspondingly corrected for barometric pressure and applied as constants in these equations the voltages observed by Scott for starting the loss on small wires were in no wise predicted. Upon thinking over the probable causes for this, it seemed that the reasons were most likely as follows:

The dielectrically powerful atmospheric film surrounding the small wire would cause the initial rupture to occur at a distance from the surface of the conductor entirely appreciable with respect to the radius of the conductor, in which event some value of D' different from D_0 would be responsible for the initial rupture of the atmosphere. The value of D' would be indeterminate so long as we have no means for determining the distance from the surface of the conductor at which the initial rupture occurs. Again, it was apparent that the values of D' and the distances at which they occur from the surface of the conductor might vary in an unknown manner relative to the radius of curvature of the conductor.

It became evident that a series of experiments would be necessary in order to obtain all of the data required to write properly the formulas expressing the relation of all the factors that control the start of the atmospheric loss between wires.

It was determined first of all to check by experiment the impression gained from the observations of Scott that the visual appearance of the corona or brush discharge on the wire occurs simultaneously with the initial formation of energy-loss, as the line voltage is raised; and to observe the nature of the charging current with respect to the line-voltage with a view to determining more data regarding the origin of the loss. Should the start of the loss be accompanied simultaneously by the visual appearance of the corona over the wire, this would be an easily discernible fact that would greatly facilitate subsequent experimental work. The point at which the atmospheric conduction-loss would occur in relation to diameters of conductors, their distance apart, applied voltage, barometric pressure, temperature, moisture, and the thickness of the dielectrically powerful but thin zones of atmosphere could then be noted simply by watching for the appearance of the corona.

For this purpose it was realized that the most convenient and effective laboratory arrangement of the line would be to suspend a single wire for observation at the center of a metallic tube of suitable diameter much the same as originally suggested by Mershon. There are three evident advantages which this arrangement has in laboratory work of this character over the use of a pair of parallel wires.

1. The dielectric flux established about the wire between it and the cylinder is easily and exactly estimated in terms of the dimensions of the wire and cylinder and the dielectric flux-constant or specific inductive capacity of the atmosphere. The flux emanates uniformly from the wire, thus making definite the results deduced from observations.

FIG. 3.

2. A lower voltage suffices to cover a given range of experimental study.

3. The tube may easily be made to contain atmosphere at various pressures, temperatures, and degrees of entrained moisture.

At this stage of the work in April, 1903, Mr. H. C. Ford, a senior student in my classes, assisted by Mr. C. L. Wernicke undertook as a thesis to make the experiments. The author is greatly indebted to these young men for the energetic and effective manner in which they did the work.

They erected apparatus, determined and charted results as follows:

The general plan for observing the details of the corona and loss phenomena due to high voltages with the aid of a cathode-ray wave indicator is given in Fig. 2. A brass wire 0.049 inch in diameter was mounted at the center of a galvanized sheet iron tube 15 inches in diameter and 14.5 feet long, as shown. Between this wire and the tube high pressure was applied and adjusted to any desired value up to 80 000 effective volts by means of the transformers as shown.

The arrangement permitted the coils C' of the wave indicator to be inserted by means of a switch, as shown, in series with the

FIG 4

wire so as to indicate whenever desired the charging current set up from the wire to the cylinder. In order to note at a glance any departure of the wire charging-current the charging-current form that should exist if no atmospheric conduction were present, a 0.75 inch brass rod with well-rounded ends was placed outside the cylinder and connected through the switch to the same terminal of the transformer as the wire. The arrangement was such as to permit quickly the switching of the indicator coil C', in series either with the wire or rod Then at low voltages prior to the disruption of the atmosphere about the wire, the indicator

diagram produced by the wire and rod-charging currents were adjusted to equality by moving the rod in its position relative to the cylinder.

A-sine wave current controlled by a proper circuit of inductances and capacity and passed through C'', produced the known indicator motion.

In the use of high voltages in this manner two precautions must be taken in the use of the wave indicator. It must be entirely enclosed in a potential-guarding screen set up on high-voltage insulators and a connection must be made from the screen to

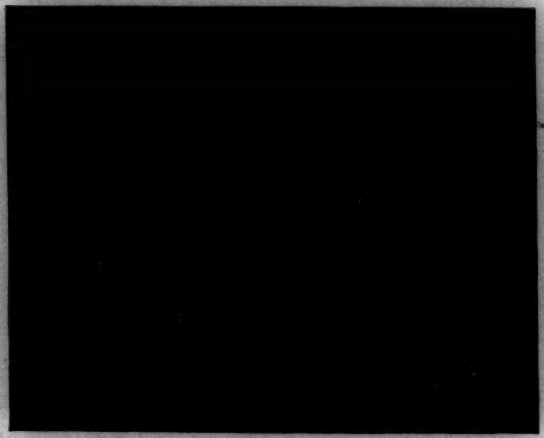


FIG. 5.

the terminal of the transformer that is connected to the wire and capacity-rod. The sine-wave current must pass through an insulating transformer and the secondary must be connected to the guard screen so as to protect the low-voltage source and relieve the indicator of electric stress at all points.

A three-phase source was employed so as to draw for convenience the sine-wave current through an induction phase adjuster as shown. By shifting the sine wave, any intricate part of the unknown wave was made to occur when the sine wave was pass-

ing through zero and, therefore, changing most rapidly, thus unfolding the intricate portion of the unknown wave so as to be observed and recorded to best advantage.

Figs. 3, 4, 5, and 6 are half-tone reproductions of diagrams of line-wire and capacity-rod charging currents, photographed from the screen of the indicator. Eight of these were observed

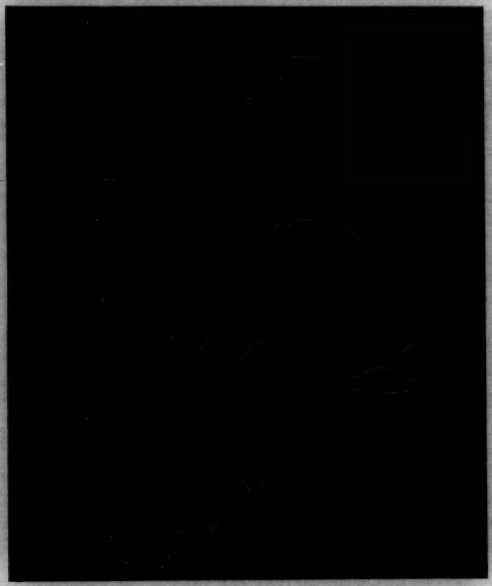


FIG. 6.

in this series at maximum voltage wave values varying from 23 000 to 48 000 volts. To give a clear idea of the characteristics of these diagrams it is necessary to reproduce only the above four.

In Figs. 3′, 4′, 5′ and 6′ the waves indicated in Figs. 3, 4, 5 and 6 are drawn to scale in rectangular coördinates. They show at once the nature of the phenomena of atmospheric conduction

giving rise to a loss between wires at high alternating voltages.

The waves of line and condenser charging currents are identical in Figs. 3 and 3′, which were observed at a voltage having a maximum value of 23 000. The voltage was not yet high enough to cause the atmosphere about the line-wire to break and become conductive. The charging current applied from the wire to the cylinder was identical with the true capacity charging-current from the rod to the cylinder.

When the voltage was slightly raised, a well-defined though small change in the line charging current appeared as a hump on either side of its indicator diagram, (see Fig. 4), or a sudden increase in the current, just as it was about to pass through zero, as seen in the rectangular coördinate diagram of this same wave shown in Fig. 4′.

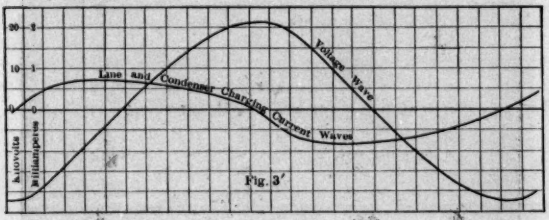


FIG. 3′.

At exactly the same value of voltage at which this hump in the line-current appeared the corona became visible when viewed in the dark, thus settling definitely this point and providing a convenient and reliable guide in subsequent experimental studies.

It should be observed that the manner of departure from normal capacity-form of the line charging current is much as one would expect from prior knowledge. After the phenomenon has been started, at that instant in each cycle when the voltage attains a value of 20 000, the atmosphere about the line-wire breaks and forms a conducting envelope about the wire. As the value of the voltage is very near the maximum it follows that the disrupting dielectric strain can last but a brief portion of a cycle. Beyond this the normal true capacity condition will be resumed in which the rod and wire charging currents are again

in agreement. The atmospheric conducting action in this instance, then, is to increase the capacity of the wire by covering it with a high resistance conducting envelope during that portion of the cycle in which the instantaneous voltage is high enough to maintain in the atmosphere next to the line-conductor a state of strain sufficient to maintain disruption.

Thus it is seen that the electric circuit from the wire to the cylinder changes during the cycle from a state of true and unvarying capacity to one of increased and variable capacity in series with a high resistance.

These two actions evidently contribute to the same result; viz., the establishment of a component of current passing from wire to cylinder that is in phase with the voltage and which, therefore, dissipates energy in heat at a corresponding rate.

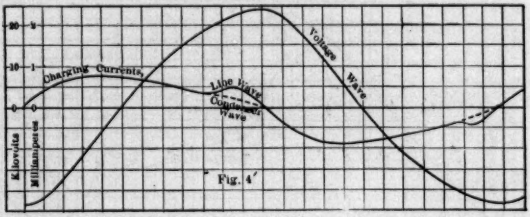


FIG. 4'.

We did not succeed in starting the hump in the line-current wave at a lower voltage than that applied for Figs. 4 or 4'. By raising and lowering the voltage and watching the indicator it was evident that it required a slightly higher instantaneous voltage to start the conduction than that required to maintain it. It is highly probable that the high temperature reached by the conducting envelope, due to heat produced by the current, will account fully for this.

As the voltage is raised the departure of the line charging-current from its normal true capacity form occurs to a remarkable degree. The maximum value of the voltage-wave was set at 26 500 volts and the card of Fig. 5 was obtained from which the waves of Fig. 5' were determined. Qualitatively, there are here observed precisely the same phenomena as in Figs. 4 or 4'. The atmosphere remains conductive during a large part of the cycle

returning to the normal with corresponding coincidence between the condenser and line currents during the remaining small portion of the cycle. It may be noted that whereas 20 000 instantaneous volts were required to maintain a minimum corona in the condition that produced Figs. 5 and 5′, the definitely lower value of 17 000 volts is required due again probably to the higher temperature of the ruptured atmosphere.

When the voltage wave was raised to the maximum value of 48 000 volts, the cards and corresponding waves in Fig. 6 and 6′ were obtained, while the disruption evidently occurs at 17 000 volts as before. So important a part is now taken by the resistance and fluctuating capacity that there is no longer a continuation at any point throughout the cycle of coincidence between the capacity rod and line-wire charging currents.

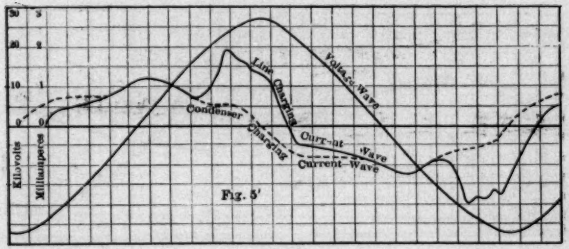


Fig. 5′.

These voltage-waves were determined by integrating the capacity rod charging currents. Their scale was obtained by observing the maximum values by means of a spark-gap. The wave-indicator scale for the currents in the case of each card was easily obtained from the effective value of the sine-wave current read from an ammeter connected in circuit with the coil C''.

In all, eight of these cards were taken and worked up in the foregoing manner. Products of the current and voltage waves were made and averaged by integration so as to obtain the watts lost in corona display over the wire at each corresponding alternating voltage applied. These results were charted in Fig. 7, locating the curve there drawn.

The way was now clear to determine experimentally the validity of the expression derived above, provided there was

some method for determining the distance from the surface of the conductor at which the initial break occurs. I am indebted to Mr. B. T. McCormick, a senior student in my classes last year, for a method by means of which this may be accomplished. Assisted by Mr. C. L. Gillespie he applied it to many of the commeccial sizes of conductors ranging in diameters from 2 to 625 mils. At the center of the 15-inch cylinder conductors of various diameters were mounted. An alternating voltage was applied

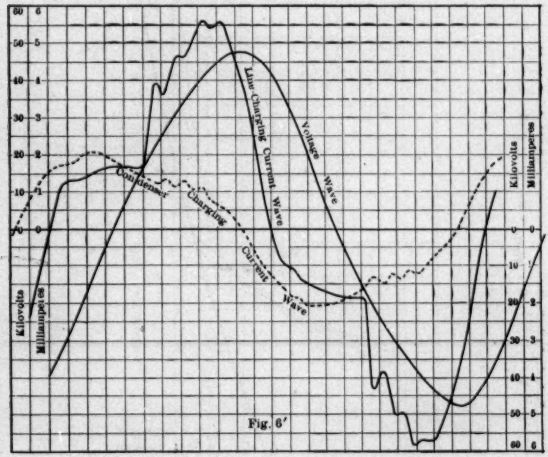


FIG. 6'.

between the conductor and the cylinder and elevated to the point at which corona is first visible in the dark. The diameter of the conductors and the maximum value of the voltage waves were observed by means of the spark-gap. Corresponding to each conductor and the maximum value of the voltage at which its corona was initially formed, curves were located showing the relation between the dielectric flux-density and radial distance from the surface of the conductor. These curves were then plotted in rectangular coördinates in the

same manner as shown in Fig. 8. The envelope of these curves when taken at sufficiently small intervals of conductor sizes, gives the relation between the distance from the surface of the con-

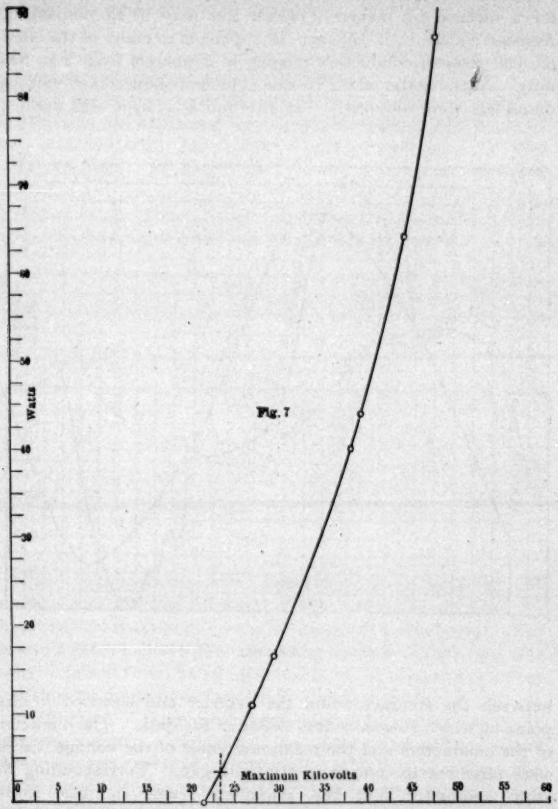


FIG. 7.

ductor and the dielectric flux-density at which the atmosphere first ruptured. In this manner the relation between the conductor-diameter, distance from surface and dielectric flux rup-

turing density, was determined The values thus determined are given in the Synopsis; *i.e.*, in the tables on page 4.

One especially interesting feature of the results given in this table is that the distance from the surface of the conductor at

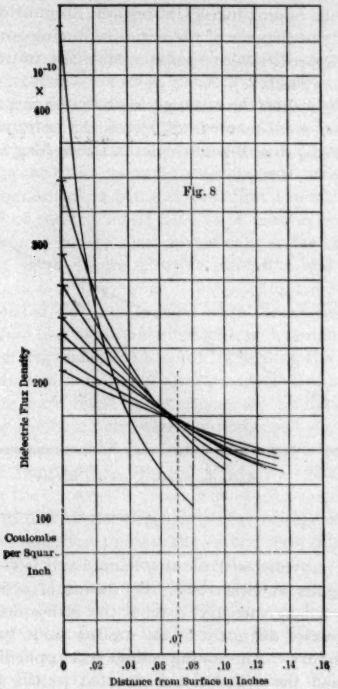


FIG. 8.

which the atmosphere first ruptures is constant at 0.07 inch. for all diameters above 0.25 inch and the corresponding rupturing flux value is constant at 170×10^{-10} coulombs per square inch. The largest conductor used in these experiments was 0.625 inch

in diameter. It is, however, reasonable to expect that since there is no change in the value of d due to changes in the conductor-curvature when the diameter varies from 0.25 to 0.625 inch, there will be no important change in such value of d for conductors of larger diameters. At conductor-diameters smaller than 0.25 inch, there is approximately a regular diminution with the diameter, of the distance of the initial rupturing-zone and a corresponding approximately regular rise in the initial rupturing dielectric flux-density.

To study the effects due to varying barometric pressures and temperatures, a conductor 0.125 inch in diameter was mounted at the center of a stout brass cylinder 20 inches long and 8.75 inch

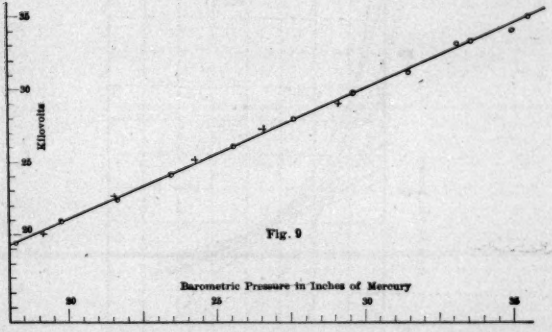


Fig. 9

in diameter, provided with packing flanges and closed with 0.5 inch plate-glass at either end. By means of ordinary hand-pumps and a long mercury U-tube, the atmospheric pressure could be adjusted definitely to any desired value from 18 to 36 inches of mercury. Alternating voltage was applied between the conductor and the cylinder and elevated to the point where the corona was observed in the dark to appear suddenly. The effective values of the voltage were determined by means of a Weston alternating-current voltmeter applied across the terminals of the low-voltage primary of the high-voltage transformer. Throughout all experiments the form of the voltage-waves was approximately the same; viz., that given in Figs. 3′ 4′, 5′ and 6′; frequency 130 cycles.

With the atmosphere in the cylinder at the room-temperature of 70° fahr., the observations showing the relation between corona starting-voltage and atmospheric pressure were made that are found charted in Fig. 9. They locate a right-line relation, the equation of which is

$$K_v = 0.902\,b + 2.93 \qquad (11)$$

wherein

K_v = effective kilovolts required to start the corona.

b = barometric pressure in inches of meroury.

To determine the effect of variation of temperature upon the voltage required to inaugurate the corona, the air in the tube was heated electrically and cooled by immersion in a salted ice-pack. However, the salted ice method for cooling was not a success and had to be abandoned, it being evident that a much more extensive method of cooling would have to be used in order to maintain the surfaces of the glass plates closing the tube free of moisture, so as to ensure effective insulation and clear vision for the detection of the corona. The cooling facilities that are evidently needed were not at hand when these tests were made, last May, so we had to be contented with such temperature variation of the air as could be obtained by heating the tube electrically by means of a jacket of German-silver wire and asbestos. Observations were made to determine the combined effects of temperature and barometric pressure variation by heating the air in the tube to about 200° fahr., at a given barometric pressure, then as the temperature dropped slowly by radiation and by maintaining the barometric pressure constant by use of the pump or by natural flow of the atmosphere, the voltage at the various temperatures required to start the corona were observed. The process was then repeated for another barometric pressure until finally observations had been made covering the temperature range of from 70° fahr., to near 200° fahr., at barometric pressures ranging from 19 to 34 inches. The humidity present was that due to natural causes and was not observed.

A target-diagram of these observations, including those made at 70° fahr., is shown in Fig. 10. The observations made at room-temperature are much more reliable than those made at other temperatures. The reason for this is the uncertainty of the actual temperature of the atmosphere in contact with the conductor at the center of the tube when at a different temperature from that of the outside atmosphere. The difference in temperature causes a transfer of heat from one side to the other

that occurs largely by means of convection currents that give rise to the uncertainty of the temperature at the center of the tube. However, the observations made at the constant barometric pressures of 29, 26.5 and 19 inches of mercury left no doubt of the nature of the barometer temperature-voltage variation as shown by the lines thus located in Fig, 10 and which indicate a close agreement between the variation of the corona-forming voltages and the atmospheric density.

The fact that there is an addition-constant in the equation for the barometric pressure-kilovolt line for 70° fahr., in equation (11) shows that the barometric pressure-temperature-corona-forming voltage relation of Fig. 10, will not be accurately expressed in a formula which assumes that the corona-forming voltage varies

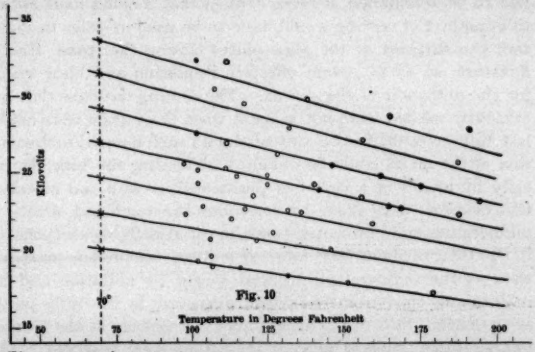


Fig. 10

The constant barometric pressures at which the lines in this diagram were located are, beginning at the top : 34, 31.5, 29, 26.5, 24, 21.5, and 19 inches of mercury.

exactly as the density of the atmosphere. However upon trial it was found that the assumption that it does so vary will provide an expression giving the results charted in Fig. 10 with sufficient accuracy for practical purposes.

The corresponding correction-factor to be applied to equation (9), to account for barometric pressure effects different from 29.5 inches of mercury and temperatures different from 70° is

$$\frac{17.94\,b}{459+t}$$

wherein

b i the barometric pressure in inches, and

t th temperature in degrees on the Fahrenheit scale.

The final equation which allows for all important factors showing the relation between the instantaneous maximum voltage, size, and separation of conductors, rupturing value of dielectric flux, and distance from the surface of the conductor at which the rupture occurs, causing initial corona formation should, therefore, be written

$$E_{max} = \frac{17.94\,b}{459+t} \times 2055 \log_{10}\left(\frac{s}{r}\right) D' \,(r+d) \times 10^{-10} \qquad (12)$$

A determined effort was made to observe the effect upon the point of initial corona formation due to the presence of moisture in the atmosphere. The ordinary air in the tube was displaced with dry air and the corona-starting voltage was then observed. Steam was then admitted to the interior of the cylinder and after allowing sufficient time for the water that was not absorbed by the air to settle upon the walls of the cylinder, the corona voltage was again observed. By this method the effect of the presence of humidity could not with certainty be detected, leading one to conclude that such effect if it does exist is small.

Where the conductors are 0.25 inch or larger in diameter, D' and d remain uniform at

$$D' = 170 \times 10^{-10}, \textit{ coulombs per sq. in.}, \text{ and}$$

$$d = 0.07 \textit{ inch}$$

and equation No. (12) becomes

$$E_{max} = \frac{17.94\,b}{459+t} \times 350\,000 \log_{10}\left(\frac{s}{r}\right) (r+.07) \qquad (13)$$

The data for Mershon's experimental line are

s = 15, 22, 35, and 52 inches.
r = 0.081 inch.
D' = 200×10^{-10} coulombs per sq. in.
d = 0.035, inch.
t = about 60° fahr.
b = about 20 in.
1.71 = approximate ratio of maximum to effective value of voltage wave.

Upon substituting these values in equation (12), the following results are obtained.

Separation of Lines.	Effective Voltage at which Initial Corona Loss Occurs.	Mershon's Observations. Effective Voltage.
Inches.		
15	43 600	43 500
22	46 800	47 000
35	50 700	49 000
52	54 000	53 500

In this table the values labelled " Mershon's Observations " were taken at the point of intersection of the voltage base-line in Fig. 1 formed by the broken-line extension of the vertical portion of the loss-curves. Mershon's conclusion is that the small loss portion, *i.e.*, the horizontal portion of these loss-curves, is due to the line insulators while the large increase of loss beyond the sharp rise in the curve is due only to the atmospheric loss. The laboratory tests confirm this fully. Some will insist that if this is strictly so the sudden rise in the loss-curve should make an abrupt and not a gradual turn upwards. Upon further thought it must be evident, however, that as the voltage is raised atmospheric conduction will first appear over the sections of the wire in contact with the insulators which have a higher specific inductive capacity, *i.e.*, a higher permeability to dielectric flux than the atmosphere, causing the electrostatic field about the wire in the neighborhood of the insulators to be higher than in a position remote therefrom. On this account the initial start of the atmospheric conduction-loss will not appear abruptly when the voltage is increased gradually through the corona-forming value. It is to be noted that the vertical portions of these loss-curves as extended to the base of the diagram, form curves having substantially the same character as the corresponding laboratory loss-curve given in Fig. 7. It is from this point of view that the above method was employed for locating the value of the voltages that started the corona losses on the Telluride line.

Professor Harold B. Smith has erected an experimental high-voltage line at Worcester Polytechnic Institute, 250 feet long, upon which conductors have been mounted varying in size from No. 10 to No. 2 B. & S. G. and high-voltage losses have been measured, due to electromotive forces ranging from low values to

upwards of 250 000 volts. He has very kindly given me three of his voltage-line-loss curves taken from these lines, arranged as follows:

Length of lines, 250 feet. Observed May 14, 1901; May 3 and 28, 1902. Barometric pressure 29.5 inches; temperature, 70° fahr.

Curve No. 1. Size of wire No. 10 B. & S. gauge. Separation 30 inches, voltage-line losses measured over a range from 30 000 to 100 000 volts.

Curve No. 2. Size of wire No. 2, B. & S. gauge., separation 24 inches, voltage-line losses measured over a range from 30 000 to 145 000 volts.

Curve No. 3. Size of wire, No. 2 B. & S. gauge., separation 48 inches, voltage-line losses observed over a range from 30 000 to 150 000 volts.

For a No. 10 B. & S. gauge wire:

$$d = 0.018 \text{ inch.}$$
$$r = 0.05095 \text{ inch.}$$
$$D' = 275 \times 10^{-10}.$$

No. 2 B. & S. gauge wire,

$$d = 0.07 \text{ inch.}$$
$$r = 0.1288 \text{ inch.}$$
$$D' = 170 \times 10^{-10}.$$

Substituting numerical values in equation (13) for the two No. 2 lines and in (12) for the No. 10 line, the following results are obtained for comparison with the measurements by Smith. (See table on page 304.)

Smith's voltage-measurements were made with a special and highly satisfactory form of electrometer. Strict agreement of the calculated and effective results cannot, however, be expected without a knowledge of the ratio of the maximum to the effective values of the actual high-voltage waves impressed upon the line. The last column in the above table gives these corresponding maximum effective ratios that would bring the calculated and experimental results into exact agreement. The ratios indicate the use of a somewhat peaked line-voltage wave which is apt to be the case owing to the distortion produced in the high-pressure transformer by the delivery of the line charging-current.

Naturally the conductor having a circular exterior section is the one best adapted, other things being equal, for the avoidance of atmospheric loss. The ordinary stranded cable exposes nearly a circular sectional area, so that in respect to the avoidance of this sort of loss the cable should give substantially the same

results as the solid conductor. Evidently when the voltage is such as to demand a greater exterior diameter of conductor than that corresponding to the solid section required for the economical or efficient transmission of the current, the solid or stranded

Line.	$E_{max.}$ Maximum instantaneous voltage at which corona loss occurs, determined by equations (12) or (13).	$E_{ff.}$ Reduced from $E_{max.}$ by the factor $\sqrt{2}=1.415$	$E_{ff.}$ Observed by Smith. (Located by intercept upon voltage axis of voltage-watt curve as was done in connection with Mershon's curves, Fig. 1.)	$\frac{E_{max.}}{E_{ff.}}$ As a factor in lieu of $\sqrt{2}$ required to bring calculated and observed results into exact agreement.
No. 10 B. & S. G. 30 in. separation.	107 700	76 000	66 000	1.63
No. 2 B. & S. G. 24 in. separation.	158 000	112 000	100 000	1.58
No. 2 B. & S. G. 48 in. eparation.	178 500	126 000	110 000	1.61

conductor can be made hollow or provided with a non-conducting core. A few observations were made by using round, hexagonal, and square conductors at the center of a 15-inch cylinder for the

purpose of obtaining comparative data, applicable to the corona-forming voltage as affected by those forms of sections. These observations are charted in Fig. 11, from which it is seen that while the exterior surface and total section of the hexagonal conductors are greater than for the same thicknesses of round conductor, yet the corona-losses are started at lower voltages. The same is true naturally to a greater extent for the square conductor. The cause of this is obviously due to the concentration of the dielectric flux at the surface-angles of the non-circular sectioned rods.

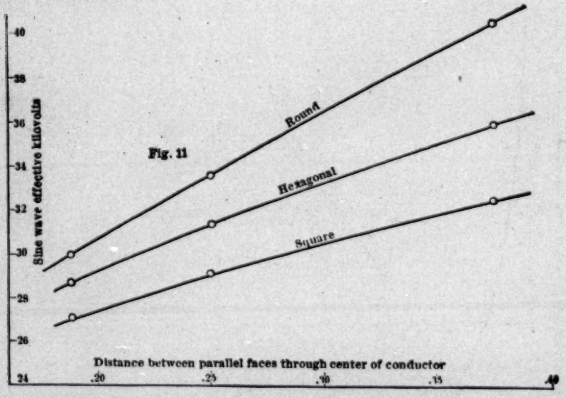


Fig. 11

The curves in Figs. 12 and 13 were determined from observations made in the thesis work of Ford and Wernicke, and McCormick and Gillespie. They are reproduced here because they constitute original data that are useful for analogous purposes other than those to which they were applied in this paper. The curves labelled "Sine Wave Effective Kilovolts" give the relation between the voltages and diameters of conductors mounted at the center of the 15-inch cylinder at which initial corona occurred for a diameter range of 3 to 600 mils. The remaining curves give the corresponding calculated dielectric flux-densities at the conductor surfaces. The voltages were determined by a spark-gap discharger having a scale laid off in terms of sine wave effective volts.

A SUBSTITUTE FOR THE SPARK-GAP METHOD FOR GAUGING THE MAMIXUM VALUES OF HIGH VOLTAGES.

The maximums of the highest alternating voltage-waves may

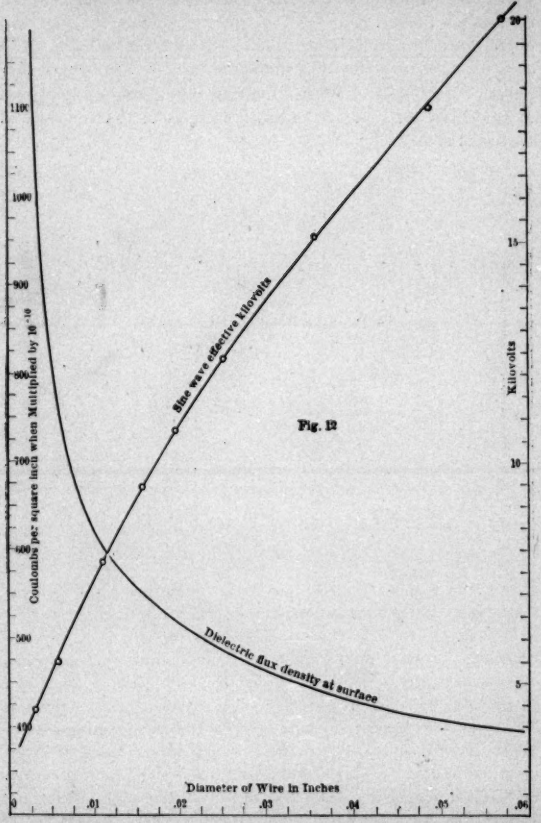


Fig. 12

be gauged easily when applied between wires of suitable diameter the separation of which is adjusted until the initial corona appears

in the dark. From the conductor diameter and separation, barometric pressure and temperature, a determination of the

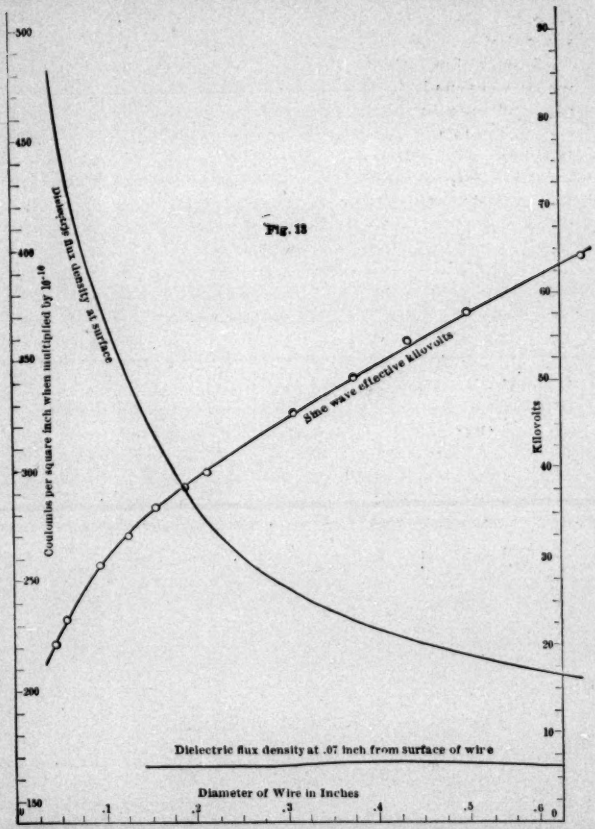


Fig. 13
Sine wave effective kilovolts
Kilovolts
Coulombs per square inch when multiplied by 10⁻¹⁰
Dielectric flux density at .07 inch from surface of wire
Diameter of Wire in Inches

maximum of the voltage-wave may easily be made that will be just as accurate as the constants in the equation (10), or the location of the curves in Figs. 12 and 13, or made with such

increased accuracy as will be obtained in similar determinations in the future. This method is free from the fluctuating indications and objections that attend the use of the spark-gap, while its only real objection is that the observations must be made in a place that is moderately dark.

In conclusion, attention is called to the fact that no experiments were made to determine the effects that the presence of rain and snow in the atmosphere have upon the point of initial corona formation. It appears from Mershon's Telluride results that there will be little effect from this cause.

With regard to the effect of the presence of smoke it should be said that there is evidence that a very slight loss is produced at all voltages, which is greater at the higher values due to this cause. During the spring of 1903, on days when the atmosphere was very smoky on account of neighboring forest fires, Dr. Blaker observed in the Physical Laboratory at Cornell that the conductive discharge through the atmosphere was appreciable when a continuous voltage of 15 000 was applied between wires of such size and separation that no detectable conduction occurred when the atmosphere cleared.

Those who have made line observations and who may use them to check the results given in this paper, must not fail to eliminate, first, the effects due to the presence of the supporting insulators.

It is altogether unlikely that changes in frequency, even over wide ranges, will affect appreciably the voltage at which atmospheric conduction is started when all other conditions remain the same.

Discussion

C. F. Scott:—The paper we have just heard read is a remarkable one, and will probably be considered unique among the papers presented to our Institute. Our papers usually deal with results that have been accomplished, or with various methods of accomplishing ordinary engineering objects. This paper is of another order—it reaches into the future, and explores the unknown field of high-pressure work.

We can properly consider the work that has been done in high-pressure transmission in the light of an advance into an unknown and undeveloped country; some progress is made each year; within the last dozen years, pressures have risen by thousands and tens of thousands of volts; with each increase of pressure, new difficulties have arisen—new phenomena have appeared, new problems have come to the designer, to the operator, and to the experimenter. The paper is of particular interest, as it deals with things outside the present range of commercial practice, but toward which engineering work is now fast approaching. If this paper had been presented 15 or 20 years ago, it would probably have been regarded by the practical engineering world as visionary—something in the nature of static electricity, and something that active, practical people have little to do with; but to-day, engineering work is very near to those limits at which this paper indicates certain physical barriers to the further advance in power transmission.

The mention of the speaker's name in the paper, suggests some reminiscences of early work on this subject. It was about ten years ago that the need of experimental investigation of very high pressure became evident; little or nothing was known regarding insulators for high-pressure work, and it was a question whether there might not be some new kind of phenomenon involved which was not then understood. At that time, the maximum pressure of transmission apparatus was about 10 000 volts; the experimental work involved the manufacture of a high-pressure transformer, the making of tests on insulators and lines, and the exploring, in a general way, of the phenomena of high pressures. A transformer of 40 kw.—then quite large—was built, for a pressure of 40 000 volts at one step, and was used in the various tests. Discharges from the surface of insulators were noted; some of the lines that were run in the laboratory were 25 to 30 feet long, composed of small wires strung four or five inches apart, alternate wires being connected to the opposite terminals, making a network of high-pressure wires. As the pressure was raised, there was at first a slight hum, then a louder hum, and a glow, developing into a loud noise, accompanied by the smell of ozone; the appearance of light, sound, and ozone, appealing to the three different senses, meant the expenditure of energy in their production, and indicated a loss. Measurements of these losses were attempted, but the instruments at hand were not satisfactory, and the results not good.

Some time after that, as mentioned in Professor Ryan's paper, Mr. Mershon took up the work at Telluride, and succeeded, after overcoming great difficulties, in obtaining the results with which his name is connected, and which reflect such great credit upon his persistence and ability. Professor Ryan took up the problem where Mr. Mershon left it. Mr. Mershon had measured the losses, which were of considerable magnitude, and increased very rapidly above a certain critical voltage. Professor Ryan has put these results to the test of a rigorous experimental investigation, to determine the formula to express the beginning of this discharge, and has, moreover, investigated the exact nature of the discharge itself.

In the discussion of Professor Ryan's paper at Niagara Falls last Summer, the speaker took occasion to remark that his cathode ray indicator was valuable not only as a result of his research, and as a beautiful thing in itself, but also as a means—an instrument, by which results of a valuable character could be obtained. Now Professor Ryan has the honor to present to us a paper in which that instrument has been put to most excellent use.

SAMUEL SHELDON:—There are four distinctly different types of conduction through the atmosphere at ordinary pressures and temperatures; namely, the glow discharge, the brush discharge, the spark, and the arc.

The glow is blue-violet in color, is silent, forms in some cases a velvety covering over the electrode terminal, is a continuous discharge to the same extent as is the current from a primary or secondary cell, and exhibits a polar preference starting, with dissimilarly shaped electrodes, at a lower difference of electrode potential in one direction than in the other. It may be made up of an innumerable number of little convexions of electricity, as is a current which comes from any electrochemical source. The dielectric field strength at which this discharge is started has a minimum value. The discharge is maintained after this value is reached up to a certain limit, when the character of the discharge changes.

The brush is red-violet in color, gives a hissing sound, is probably intermittent in character, follows many unbranched paths which exhibit a tendency to separate from each other, and shows a polar preference similar to that shown by the glow discharge.

The spark is noisy, often follows forked or branched paths, and is often oscillatory in character. It is white in color but participates in the color of the incandescent vapors of the electrode materials. This coloring is prominent with iron electrodes and the characteristic ultra-violet radiations are very strong.

The arc discharge is familiar to all, has the color of the incandescent vapors of the electrode material, owes its conductivity largely to the presence of these vapors, and is quiet or makes characteristic noises.

The glow and the brush discharges are probably due to gaseous

ionization, and this corona discharge is probably a combination of both of these discharges. As the pressure rises, first comes the glow, and then comes the brush; and as it falls, the brush drops off and then the glow. There is a preference of polarity as shown in Fig. 4′ of the paper, where the little hump on the curve starts at a pressure of about 18 000 when the current is in one direction, and at about 21 000 when the current is in the opposite direction. This does not appear in Fig. 5′; but in Fig. 6, the pressure at the start of the prominent hump is something like 17 000, whereas the second hump starts at a little less than 20 000 volts.

The dielectric field intensity which is necessary to start a glow or a brush discharge in the atmosphere at normal conditions of pressure and temperature is smaller than that necessary to produce a spark. Therefore if the method of measuring high pressures which is suggested in the paper, be adopted, the breakdown value of 10 000 volts per inch in free air, which is the constant used in this paper and which is the value adopted by the INSTITUTE as a result of Steinmetz's experiments, should be abandoned and a new constant should be determined.

HAROLD B. SMITH:—As a discussion of this paper was not contemplated for this evening there is but one point which, possibly, may be added to an expression of most thorough appreciation which is felt for the work that has been done by Professor Ryan and of all that it signifies for the development of high-pressure work. He makes a reference in his paper to the form of electrometer which we have used successfully at Worcester for two or three years, for high-potential measurements. Some details of the way in which this electrometer was developed may be of interest. In 1901, four graduate students in electrical engineering at the INSTITUTE undertook the design and construction of a 500 000-volt transformer. In carrying out this work, we desired, after building the transformer and after getting discharges over spark gaps ranging up to four feet (1.22 metre), to measure the voltage; so it was proposed to use an electrostatic instrument measuring the voltages about the several coils of the secondary and adding them as a preliminary step. One or two of the men who were at work on this problem are in the audience and presumably they will remember the following circumstance. The electrostatic instrument registered as expected for the first few measurements, but the middle of the secondary of the transformer being earthed, as we proceeded away from the earth the readings became less and less, although it was known that the number of convolutions in the several secondary coils had been carefully counted and did not vary. A point was soon reached at which a zero reading upon the instrument was given and then reversed deflections of the electrostatic voltmeter were secured.

Proceeding from this point, the line of reasoning developed the conclusion that the absolute potential impressed upon the instrument was, in its effect, in excess of the effect due to the difference

of potential and so there resulted a repulsion of the parts of the electrostatic instrument in place of attraction as would ordinarily occur in the measurement of differences of potential. This at once led to the conception of the use of a *repulsion voltmeter* in which the fixed and movable parts were connected together and attached to a single wire leading to the instrument so as to depend wholly upon the repulsion due to the absolute potential of the system. This proved a peculiarly adaptable instrument for this work, where it was necessary to deal with potentials which would jump three or four feet, as it was necessary to lead but one wire to the instrument. Although the instrument was developed in this way, now that we have it in use it proves to be nothing more than an old-fashioned electroscope modified to meet successfully the conditions imposed by high pressures.

P. H. THOMAS:—In speaking of the apparent enlarging of the diameter of the wire to a certain pressure, does Professor Ryan wish us to think of the phenomenon as though we actually had a larger metal conductor, and that the electricity passes into the air and stays there within a definite volume? Or is it more probable that when it has once left, the wire will remain mobile, and the distance the charge passes over the surface of the wire will depend upon the time of duration of the excessive strain. If the latter is the case, we should find a difference, with different rates of alternations, unless the greater duration of time required for one alternation exactly balances the effect of the variations in a number of alternations; but the writer understands that no such difference has been found. Is this correct?

HARRIS J. RYAN:—The question cannot be answered very directly. This much, however, is certain: that one can pass very small currents through the atmosphere over large distances, with low frequencies, or with direct currents, provided that the wire is so small that the atmosphere breaks around its surface; ionization occurs, or electrons are set free, and they go from one wire to the other; but there seems to be no conduction of that character of sufficient magnitude to give rise to quantities that must be reckoned with in engineering.

P. H. THOMAS:—The speaker cannot conceive, at the present time, of a limiting surface to the air to which the electricity would go and there stop, without some further condition entering to determine physically the demarcation of the conducting space. Can Professor Ryan suggest any such idea? The air being a perfect gas, has, within itself, no force that can resist permanently at a definite point the tendency of the electricity to proceed further.

HARRIS J. RYAN:—In the experiment just cited, if the diameter of the wire is considerable at ordinary pressures, then there will be no discharge from one wire to the other. If the diameter of the wires is so small that at the pressure you apply between the wires, the atmosphere is broken around these wires, then there will be a discharge from wire to wire. In using high-pressure

continuous-current dynamos connected up in series for checking these experiments, one gets the conduction effect a little before the arc forms between wire and wire. However, with a Holtz machine you can produce a continuous pressure very much higher, and in the laboratory one can thus carry a small continuous current between small wires; for example, those having a diameter of three mils, from side to side through the atmos phere of a room. Such conduction will occur, however, only when the diameters of the wire are so small in relation to the pressure generated by the Holtz machine that structural rupture of the atmosphere occurs near the surface of the fine wires,—electrons are thereby set free, causing conduction. At certain larger conduction radii, dependent upon the pressure employed, appreciable atmospheric conduction will occur.

P. H. THOMAS:—In passing electricity through a vacuum, which is almost perfect, we have three electromotive force resistances to consider; one is the force preventing the electricity from leaving one of the electrodes, another preventing it from entering the other electrode, and the third, the resistance to passing through the vacuum space. The resistance to passing through the vacuum, with high exhaustion, is not very considerable, but is measurable. But with atmospheric pressures it must be tremendous. Have we not these elements in this case, or at least two, to consider; the force necessary to pass the current through the air and that of leaving or entering the wire? The resistance from the electrode is different from that into the electrode. If that is true, as Dr. Sheldon suggested, we should then find a difference between the positive and negative limits of the alternating current due to the electrode effect, though not the portion of the total resistance which is due to the resistance of the air. Possibly that may explain the slight difference between positive and negative which he notes. Have you found any difference between the positive and the negative?

HARRIS J. RYAN:—This matter has not been investigated and therefore the speaker has no knowledge of it. With alternating currents, of course, one conductor is first positive and then it is negative. The electrons are fired forth at one impulse and upon the following impulse they return again. With alternating current these phenomena are very hard to study. When we have very high continuous current dynamo pressures for laboratory work, those capacity phenomena that are ever present in our experiments with high alternating-current pressures will be eliminated, and with high continuous-current pressures this phenomenon can be studied with success.

P. H. THOMAS:—Different materials require radically different electromotive forces to pass electricity to the electrode. It would be interesting to study those materials which have shown the greatest differences in this connection. Aluminum and copper would be two which would have a different effect, probably. Have ou not tried these metals, to see what difference there is?

H. J. RYAN:—Probably you are right, that the constants will be somewhat different for these different metals. Iron and brass and copper were used rather indiscriminately in determining the flux densities at which coronas are established in relation to changes in the curvature of conductors, and no noticeable difference due to these different metals was found, but the subject being new, the measurements are not refined enough to study these matters to best advantage. They are important, and some one should take them up and study particularly the manner in which flux densities are different for the aluminum with respect to copper.

P. H. THOMAS:—The speaker made direct measurements with a quadrant electrometer, used as a wattmeter, of the loss into air in a 50 000 volt circuit, nearly 100 miles long, the same instrument as described by Mr. Miles Walker before the INSTITUTE at the Great Barrington meeting. The losses began to be measurable at about the same pressures found by Professor Ryan,—that is, at from 20 000 to 25 000 volts, to ground; the loss increased very rapidly.

In the measurements made, the loss at 60 000 volts between the wires was approximately 10 kw.,—an insignificant loss as far as power transmission is concerned, but, nevertheless, very appreciable.

P. M. LINCOLN:—In reading over abstract of Professor Ryan's paper on "The Conductivity of the Atmosphere at High Voltages," the questions which are apt to occur to the practical high-pressure engineer who has a line to operate are:

1—Is there any loss in my line due to the effect which Professor Ryan calls the "corona" effect. If so, how much?

2—If these losses are not taking place at present pressure, to what extent will they enter if pressure be raised?

3—If these losses are taking place, what remedies can be applied to prevent?

How far are these questions answered by the paper which Professor Ryan has presented? To the first question the answer seems to be definite and complete. We may readily determine from the formula that for the worst conditions which would occur in actual practice; viz: a No. 6 wire with a spacing of say forty-eight inches, this corona loss at sea level does not begin until the voltage has reached the neighborhood of 100 000 effective. For the maximum altitude at which transmission is apt to be carried on, say 10 000 feet above the sea level, the pressure at which the loss begins may be as low as 65 000 for the worst cases, but even then the pressure at which the corona loss begins is still considerably beyond the limits of the actual practice of to-day. The question of corona loss, therefore, is evidently one for the future to decide and not one which should disturb high-pressure engineers of to-day.

The formula which Professor Ryan gives at once tells us the pressure at which this corona loss begins to appear, and the other data cited apparently checks this formula closely. The

voltage at which this loss begins depends upon barometric pressure, temperature, radius and spacing of the wires, and upon two additional quantities designated "d" and "D'." These two last mentioned quantities are, so far as can be judged, from the abstract at hand, empirical in their nature. The pressure at which the loss begins is apparently entirely independent of frequency.

When we come to the second question, the answer is not so complete. To know the pressure at which this form of loss begins is of course important but it is even more important to know how much it amounts to for any given voltage excess above the point of beginning. For one particular case, which by the way is entirely outside the realm of practice, Fig. 7 gives the answer. What the relative losses are, however, for conditions which would occur in practice the paper leaves undetermined.

Normal progress is bound to carry transmission pressures beyond those that exist to-day, therefore the third question as to remedies to apply has a decided bearing. It is well known that a good rubber insulation on the wire will almost entirely prevent this corona loss, at least within the lower limits of pressure at which the effect occurs.

It would be interesting to determine the effect of various kinds of insulation on the wire, in so far as their influence in preventing this loss is concerned.

The method applied by Professor Ryan is most ingenious and we hope that the record of the work done by him which is given in this paper is not the last which will be done along similar lines.

[COMMUNICATED AFTER ADJOURNMENT BY G. T. HANCHETT.]

In 1895 the writer investigated the visible phenomena surrounding the electric discharge, and having no large sources of potential at hand, used an ordinary 1-inch induction coil, and viewed the discharges under the microscope. Two terminals of thin metal foil were gummed to the slide of the instrument, and arranged so that they would appear in the field of a 0.25 inch objective, and passed discharges between them of varying strength. One of the most interesting points developed was that the negative terminal was distinctly hotter than the positive terminal, and when the discharge had reached the sparking point, the negative terminal melted very rapidly, while the positive remained practically intact.

Professor Ryan's investigations of the effect of temperature on the dielectric strength of air, together with this phenomena, seem to explain Dr. Sheldon's remarks about the difference of potential required to strike between a knob and ball. When the point is the negative, the heat developed there is concentrated, the temperature is high, and the air breaks down easily at a low pressure. When the point is positive, the heat developed by the discharge, being large at the negative pole, is readily radiated by the large surface of the ball, the temperature is lower, and the discharge does not find as easy a path.

Concerning Mr. Scott's remarks about the ozone that is generated, it might be interesting to add that in case of direct currents it is easily shown that ozone is generated in larger quantities at the negative pole. The most convenient means of detecting this is a solution of starch and potassium iodide.

Not the least feature of interest in Professor Ryan's paper is his denial of the theory that a moist atmosphere necessarily involves great leakage. His experiments conclusively show that this is not the fact, and we may therefore attribute any additional leakage which our lines experience in moist weather entirely to the accumulation of moisture on the insulators, and not at all due to the increased tendency to brush discharge leakage through the atmosphere itself.

[COMMUNICATED AFTER ADJOURNMENT BY ELIHU THOMSON.]

The paper of Professor Ryan brings out clearly the relation between the different factors which combine to influence the voltage at which atmospheric loss begins or becomes serious. He has been able to deduce a formula for calculating that voltage under varying conditions of atmospheric pressure, temperature, etc. The data obtained by Mr. Mershon and Professor Smith are shown to fit in with Professor Ryan's results. As he points out, the lower values of effective voltages obtained in the Smith observations are without doubt due to the distortion of the wave form into one more peaked. The true character of the atmospheric loss is pointed out by Professor Ryan in connection with his very interesting plottings in Figs. 3′, 4′, 5′, and 6′. The loss is due to an enlarged capacity-current working over the high resistance layer, which virtually adds to the diameter of the conductor. The addition of this broken-down air layer takes place at a critical voltage and its amount rapidly increases with any increase beyond the critical value. In Fig. 6′ the effect is that of a greatly enlarged capacity coming into existence at something under 20 kilovolts in Professor Ryan's experiment, if the writer correctly interprets the results. In Fig. 3′ the voltage wave attains a maximum of 22 kilovolts without showing the indications of atmospheric loss. Increasing the voltage as in Figs. 4′, 5′, and 6′, shows that the upward bend of the charging current curve begins at a value considerably below 20 kilovolts. This may be due to ionization or heating of the air layer by the prior waves. If this be true it should become more pronounced at higher frequencies. It might probably be a useful extension to study the effects when the conductor was kept hot and cold air circulated about it, and also the result when the conductor being maintained at a much lower temperature than the surrounding air. The highly interesting and practical results obtained by Professor Ryan serve as an illustration of the value of the inertialess cathode ray wave indicator in the development of which he has succeeded so admirably.

[COMMUNICATED AFTER ADJOURNMENT, DISCUSSING "THE CONDUCTIVITY OF THE ATMOSPHERE AT HIGH VOLTAGES."
BY RALPH D. MERSHON.]

This paper takes up a number of points which the writer was desirous of attacking at Telluride, but which lack of facilities prevented.

The fact that the critical point in the loss curve; *i. e.*, the point at which the atmospheric loss suddenly begins, is marked by the beginning of luminosity was appreciated by the writer in the Telluride work, and made use of to a slight extent in studying the question as to the influence which the material and the condition of the surface of the conducting wires had on the critical point. It was found that the condition of the surface as to its roughness had a very decided bearing on the critical point, any roughness causing it to occur at a much lower voltage than with a smooth surface. There was apparently also some difference in this regard due to the material of the conductor.

Luminosity, however, is not the only evidence of the critical point. The rustling or crackling sound, very apparent in the case of an overhead line, is also coincident with it; also, curious as it may seem, the critical point is indicated very accurately by the twitching of the hair and moustache. This was first noticed in some readings on a wattmeter inserted directly in the high-voltage circuit and over which the observer had to lean, bringing his face and body within 18 to 24 inches of the instrument. The metallic case of the wattmeter was connected to one leg of the circuit in order to take advantage of the shielding action of the case against any electrostatic influence. A number of trials showed that the observer could, with fair accuracy, tell when the critical point had been reached.

As to the question of frequency, the Telluride measurements were conducted at a frequency of 60 cycles and also at 30 cycles, but no difference could be detected which could not be laid to errors in the instruments.

There are two points in which Professor Ryan's paper is in error. The work at Telluride was done in 1896–1897; the measurements were made at voltages as high as 72 000 volts and a voltage as high as 133 000 volts was impressed upon the line. No measurements were taken, though several photographs were secured at this latter voltage.

Referring to the possible contention, mentioned on page 128 of Professor Ryan's paper, that the line-loss curves of the writer's paper should be abrupt, there are some other points in support of Professor Ryan's view One of these is that the line wires could not be absolutely the same through their length as to roughness and that at the rough portions the loss would first begin. This was very apparent when viewing the Telluride line at night. The line became luminous in spots, which at first seemed equally spaced but which closer examination showed to be unequally spaced. As the voltage was raised other luminous spots grad-

ually developed at points intermediate to the first ones, and this action continued until the whole line appeared more or less luminous but never uniformly so. The spots were never far apart, always at intervals small enough so that at a little distance the line suggested a string of luminous beads, and it shows as such in the photographs taken. Each one of these luminous beads had a bunch of fine purple streamers from it. Another reason in support of Professor Ryan's view is that an alternating e.m.f. is dealt with. At first just the top of the wave rises above the critical voltage and as the voltage is raised, more and more of the wave is effective above the critical value. This in itself tends towards a more or less gradual increase in the loss curve.

[COMMUNICATED AFTER ADJOURNMENT, DISCUSSING "THE CONDUCTIVITY OF THE ATMOSPHERE AT HIGH VOLTAGES."
BY S. M. KINTNER.]

The writer's experience with the coronal formation on high-voltage lines leads him to believe that the surface condition of the wires is a factor that enters quite largely. This condition can hardly be incorporated in any formula expressing the relation among the various factors involved. An instance of this was quite forcibly brought to the writer's attention while working with an arrangement of horizontal wires as a Hertz oscillator This oscillator had another circuit in proper relation to it to prolong the oscillations set up. The horizontal wires were bare copper, about No. 16 B. & S. gauge, carefully insulated from and parallel to the earth, at a height of about six feet, both ends of the wire oscillator being the same length. On carefully adjusting the oscillating period of the auxiliary circuit to that of the wires, as was told by two independent tests, and viewing the wires in the dark when the power was on, they were seen to glow very decidedly throughout about two-thirds of their length, the glow being strongest at the ends and tapering down to darkness towards the middle. One wire was noticeably brighter than the other. An examination of the wires showed that one was old and very much weathered—this one glowed the brightest—while the other was new and had been exposed to the weather for the first time. On the substitution of an old wire for the new, the glow was practically the same.

Another point, suggested by the reported experiences of the Marconi Wireless Telegraph Company, in which they found it much easier to send messages by night than day, is the question of the action of light, ultra violet, etc., upon the formation of the corona and line losses at high voltage. It seems most likely that there is some such action.

An examination of Professor Ryan's formula brings out the great sensibility of the coronal formation to temperature variation. A variation of 5° fahr. causing 1% variation in the voltage at which this phenomena takes place Taking as extremes of temperature variation for cases that would likely occur on transmission lines—say −25° fahr. to 125° fahr.—a range of 150°, which would mean a 30% variation in the critical voltage

DISCUSSION ON "THE CONDUCTIVITY OF THE ATMOSPHERE AT HIGH VOLTAGES," AT PITTSBURG, MARCH 10, 1904. BY H. W. FISHER.

The speaker has never made experiments to determine line losses due to very high pressures He knows, however, that unless the cable is well made, said losses can be considerable and the cables become very warm in consequence. When cables are being tested to from 30 000 to 60 000 volts, the ends have to be very thoroughly protected or else there will be long discharges over the insulation near the ends. A short time ago the speaker made a test of 55 000 volts between conductors of a non-leaded cable on a wooden reel The particular cable in question had three conductors and a test was made between one and the other two. All the spaces between the convolutions of cables were beautifully illuminated, and the noise of the discharges was loud and almost enough to make one feel nervous. The energy loss here must have been considerable because the cables became very warm.

The speaker has obtained some beautiful and extremely interesting corona effects when making measurements of the spark distances corresponding to different voltages and different kinds of points. The tendency to brush discharges is apt to cause an actual spark to take place at distances which are not always normal. To obviate this, he has used concave discs whose edges are slightly back of the needle points, and by doing this he has obtained much more uniform results.

[For further discussion on this paper, see page 168.]

BLANK
PAGE

A paper presented at the 184th Meeting of the American Institute of Electrical Engineers, New York, February 26, 1904.
Copyright 1904, by A. I. E. E.

EUROPEAN PRACTICE IN THE CONSTRUCTION AND OPERATION OF HIGH-PRESSURE TRANSMISSION LINES AND INSULATORS.

BY GUIDO SEMENZA.

In Europe, as in America, the old practice in overhead line construction has always been to consider the construction of an electric transmission line work that any man could do. It was sufficient to erect a number of wooden poles, fix on them some insulators and stretch some wires, and everything was expected to work well. The line was considered the simplest and the easiest part of the plant. It is true, on the contrary, that the line was the part which gave the greatest trouble; but the line constructors placed the blame upon atmospheric disturbances. It was only at the time of the Paderno (Italy) installation in 1895, I believe, that new views were entertained on this problem.

The new way of considering the matter, originally due to Mr. Roethlisberger, an engineer of great skill in metal frame constructions, was the following: an electric transmission line, being a structure every part of which has to bear certain strains, must come under the general head of engineering work, as would any similar structure. You carefully calculate a bridge; why should you not avail yourself of the benefit of statics and dynamics to make your line the strongest and the cheapest? No objection could be made to this simple reasoning and the Paderno line was constructed in accordance with these considerations.

Following this principle, new solutions and views were gradually entertained, and the different matters treated of in this paper are to be considered the result of a study of the subject by many engineers.

The first question which requires consideration when a line is to be built and the pressure of the current has been fixed, is; which is the most advantageous wire-section to be adopted? In a line you may allow any loss of energy, say between 2 and 20 per cent; but what will be the most advantageous value, considering both the cost of construction and economy of operation? In some instances the line-loss is limited by the regulation required

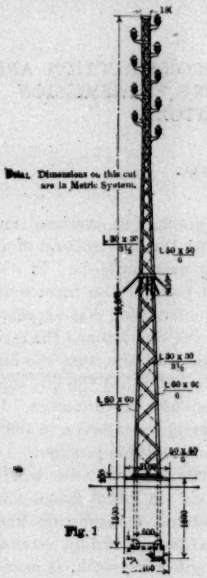


Fig. 1

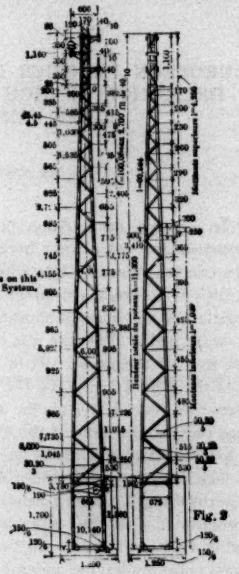


Fig. 2

at the end of the line; or in cases of small powers and high pressure, by the minimum section of the wire required to give the necessary mechanical strength; in other cases, the problem is generally purely one of economy. In the old practice, the most economical wire cross-section was determined without the aid of any calculation, in quite an empirical way based on the consideration of gross expenses, weight of wire, etc. However, a close examination of the subject shows this to be an important factor of economy.

I beg to refer you to a paper on this subject I presented to the Italian Association of Electrical Engineers, in which the problem is exhaustively treated, so I shall refer here only to the principal points. The greater the weight of copper, the less the loss; so that by increasing the wire section we incur a larger outlay of capital and annual fixed charge in order to increase the possible income. But, while the income as a function of the copper-loss follows a linear law of variation, the outlay of capital follows a hyperbolic law. Consequently, at one of the limits we arrive at zero income for a definite expense, and at the other limit a definite income for an expenditure infinitely large. Between these two limits there must be, in each particular case, a value of copper-loss for which the profit from the undertaking is a maximum or any other economical condition is fulfilled. The condition to be arrived at or to be fulfilled must be determined from the data of the problem. Supposing, then, that the following values are known, namely: power produced; cost of installation; selling price; operating expenses; the value of the copper-loss which will bring a maximum profit can be found. On the contrary, when the selling price is not fixed, the value of the copper-loss which reduces to a minimum the anunal cost per kilowatt utilized may be the quantity to be determined.

These problems may be worked out in an analytical way by writing down the equations and solving them by the differential calculus. But it is much better to draw the curves of the different elements and compose them. The graphical method permits one to take into account, in their true significance, some elements which vary according to laws we are not able to express by analytical functions: for instance, the value of poles and insulators, which is not a constant, but varies with the number and section of wires, and especially all the quantities which enter into the problem when an auxiliary steam station has to be resorted to, as, for instance, the consumption of coal, the hours of utilization, etc. Moreover, the results which we obtain by the graphical method show quite clearly the behavior of the resultant value towards the maximum or minimum found, allowing a certain latitude in their adoption. An analytical expression gives an isolated figure without showing very much of the curve to which it belongs. This method is an amplification of the well-known Kelvin law and permits one to apply the principle of this law to any case, however complex it may be. When the pressure and the cross-section of

wire have been fixed, the question of the route of the line arises. In Europe, generally speaking, important lines are carried across the country and not alongside roads; this is done for obvious reasons. The cross-country method allows the building of a straight line, thus avoiding angles to a considerable extent; then, again, the line is shorter. Of course, crossing cultivated land, as is generally the case in

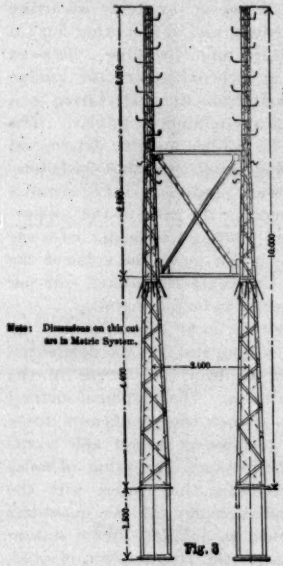


Fig. 3

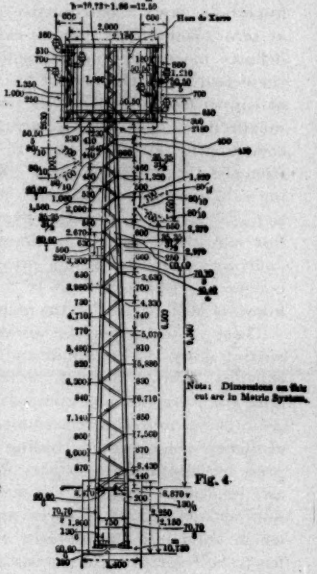


Fig. 4

Europe, the cost of building the line is increased on account of the expropriations; but in the greatest number of cases, the extra cost of purchase of land or of right of way, is more than compensated by the shorter line. It must not be forgotten that the weight of copper increases in the ratio of the square of the length of the line, the loss remaining the same. It is often argued that following the high roads, the patroling of the line is much easier, but in many cases the right of way along

the line across the fields is included in the purchase and the system proves very efficient. At all events, well-constructed and straight lines far from the roads do not show the necessity of very close patrolling, although it is prudent to exercise it.

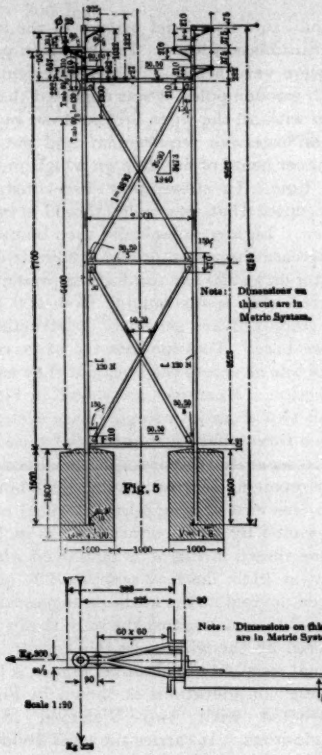


FIG. 5.

A most important question now arises: whether metal poles are better than wooden poles? The principal reason for the adoption of wooden poles is the small cost of installation. For small lines

this may be true. Another reason is the assumption that wooden poles increase the insulation of the line; and this also is true, but only when the insulators are very bad. A close investigation, however, will lessen the advantages claimed for wooden poles.

First of all, I shall submit a brief history of the introduction of iron poles for transmission lines. The first iron poles erected for this purpose were very heavy. While no calculations were made for lines with wooden poles, it was expected that iron poles should stand, even with all the wires broken down on one side of them. This was an excessive requirement and not in the least justified; I have never heard of any line on which more than one wire broke at a time. In subsequent line-construction the hypothesis was accepted that iron poles should stand with one or two wires broken. Lighter poles could then be used. It was then possible to increase the spans, previously limited to 100 feet, to 200 feet, and later on to 250 feet; and at the present time some lines are constructed with spans ranging from 300 to 400 feet.

The iron poles employed are generally constructed of lattice-work with a square base. They possess the same resistance in the direction of the line as across the line, and they can resist the strains in any direction. Examples are shown in Figs. 1 and 2.

When more than two wires in a single-phase system, or more than three wires in a three-phase system are to be used, it may be found convenient to separate the wires into two lines, in order to render possible the repairing of wires on one side while the others are in circuit. In this case the support is formed of two poles placed apart and joined by cross-connections as in Fig. 3, or a support like the one shown in Fig. 4, is employed when it is important to occupy as little land as possible. A new form of double pole has been devised at the author's suggestion.

On straight lines with equal spans, the only strain to be borne by the line is exerted by the wind. In this case it is useless to employ poles of equal resistance in all directions. A line support constructed on these considerations is shown in Fig. 5. This support is constructed with two U-shaped irons, cross-connected with angle-irons. It carries six wires divided into two sets, two metres, 6.5 feet, apart. Having a very wide base, it presents a great resistance in the direction of the wind and a low resistance in the direction of the line, in which direction it is elastic and can deflect over 16 inches without exceeding the limit of elasticity, and is called the " elastic support."

In the event of one or two wires breaking, the two nearest poles will bend, which will discharge the following spans; and calculations show that the entire line will stand and no injury will be done to the supports. These poles are employed for spans of over 300 feet and are very economical. In fact, an elastic support for six wires and for a span of 300 feet weighs about 1000 lb.

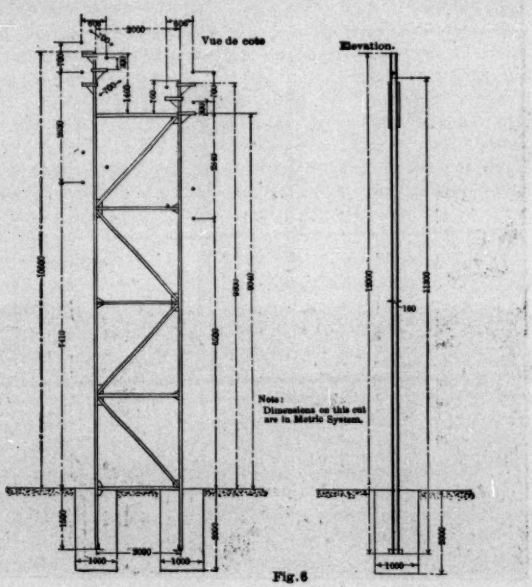


Fig. 6

I shall now enumerate the principal advantages and disadvantages of iron poles.

ADVANTAGES.

Duration—Wooden poles will last from two to ten years, according to the nature of the ground. The durability of iron poles cannot be definitely stated as yet, but they will surely last 40 years, reducing the depreciation to a small amount.

Large Spans—Spans with iron poles may reach from 300 to 400 feet and in exceptional cases to 600 feet and more. This compensates for the higher cost of single supports, as in lieu of three or four wooden poles one iron pole can be adopted, reducing the number of insulators and consequently of weak points, and thus

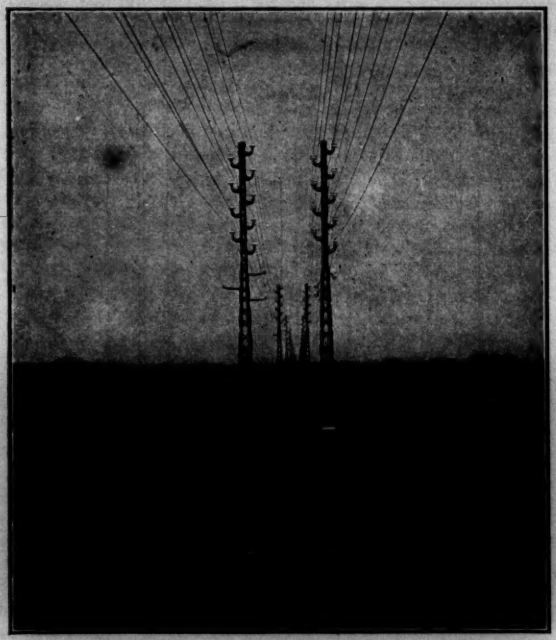


FIG. 7.

rendering possible the crossing of difficult passages, as shown in the examples which follow.

Lower Cost of Maintenance—The experience with existing lines constructed with iron poles, shows that the expense of keeping the line in proper repair and good working condition is very much reduced. With wooden poles the strain exerted

by the wires will slightly displace the poles or rotate the cross-arms. Dry or wet weather will lessen the connections between cross-arms and poles and between pins and poles. In some cases wooden poles will twist in time.

All the above facts affect the insulators, pins, and bindings, so that a certain amount of work is constantly required to keep them in good order.

In line-construction with iron poles, all these causes of deterioration are avoided and lines which have been in use from five to six years are in as perfect condition as they were when first constructed. The poles require repainting only every four or five years.

DISADVANTAGES.

A Somewhat Greater Capital Investment—To illustrate this point, I submit the following figures, showing the difference between a line constructed with wooden poles and a line constructed with iron poles, based upon European prices and for a three-wire line for high-tension transmission.

Wooden Poles.		Iron Poles.	
53 Poles at $6.00	$318	16 poles at $24.00	$384
3 x 53 = 159 Insulators with brackets, at $1.00	159	Concrete Foundation at $0.00	144
For right of land occupation, $2 per pole	106	3 x 16 = 48 Insulators with brackets, at $1.00	48
		For right of land occupation, at $2.00 per pole	32
	$583		$608

Better Insulators Required—As a matter of fact, the breaking of an insulator means a complete grounding; but as we shall see, the insulators which can now be obtained reduce the frequency of this disturbance very much. On the other hand, it is not always true that wooden poles act as insulators as, for instance, in wet weather one cannot depend upon the surface-insulation of wood. Concluding, from an economical point of view, iron poles require a larger capital investment; but the maintenance and depreciation are reduced to a minimum. These considerations tend to make the adoption of iron poles for important transmission lines more and more general.

We shall now proceed with the consideration of the best method to be pursued in the construction of a line, more espe-

cially with reference to important lines. When the land across which the line is to be constructed has been decided upon, a careful survey is made and a map drawn, on which the location of each pole is marked, the angles and eventually the prescribed height of the lowest wire from the ground. The single supports are then studied and calculated. These are divided into two classes; namely, normal and special. The normal supports are intended for small angles, equal spans, and normal height. The special supports are those which have to meet special conditions.

Iron poles are calculated by the ordinary rules of mechanics. The forces acting on the poles are: the weight of the pole itself; the wind (both on poles and wires), and the strains transmitted by the wires. With equal spans on each side of the pole and no

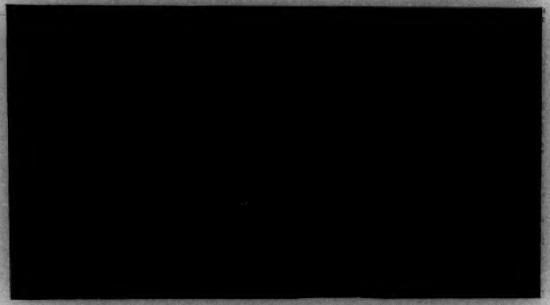


FIG. 8.

angles, the only forces acting on it are: the weight of the wires and the wind. When spans are not equal, there is a longitudinal strain which varies with the temperature. If an angle occurs, there is a component of the strain exerted by the wires which acts in a transverse direction. In the case of a vertical angle there will be a vertical component.

We must then begin with the calculation of the strains exerted by the wires. In doing so the effect of wind and snow must be taken into account, allowing a tension which does not exceed the limit of strain admitted for copper in coldest weather and with an overload of snow and ice. The maximum sag is also calculated in order to determine the height of the pole, as the wire

must never come too near the ground. Taking into consideration all the above facts and effects, the poles are calculated in the same way as any iron structure.

We must also calculate the weight of the necessary foundation, which must be sufficient to resist the overturning moment. In this calculation the resistance of the earth surrounding the concrete foundation block is also taken into account. This having been done, the profile or ground cross-section is completed, by marking on it all the aforesaid data, including height of poles,

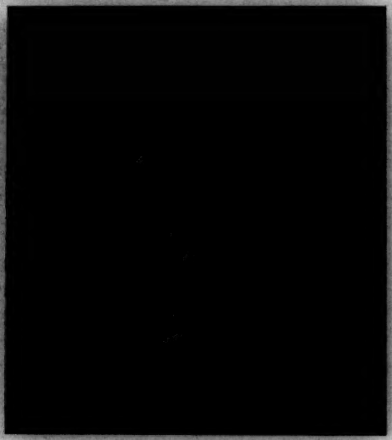


FIG. 9.

sag, strains, etc. The strains exerted by the wires being transmitted to the poles through the insulators and the pins, these must be considered from a mechanical point of view, and calculated in accordance therewith.

Wooden cross-arms are sometimes employed with iron poles, in which case any system of pins may be used; but in general, supports constructed entirely of iron are preferable. In this case either iron or steel pins are used on brackets composed of angle iron, as in Figs. 2 and 5, or even entirely of cast-steel, as can be seen in Figs. 1 and 4.

A special cement is employed to fasten the insulators to these brackets, or, in the case of small lines, tarred rope is employed. This differs entirely with American practice, and no attempt is ever made here to use threaded insulators, as it is difficult to obtain good insulators with thread of the exact gauge. The best cement that can be employed for this purpose is composed of ten parts of litharge and one of glycerine, well mixed.

The brackets and insulators cemented together with such a mixture form an indivisible unit, which must be replaced when-

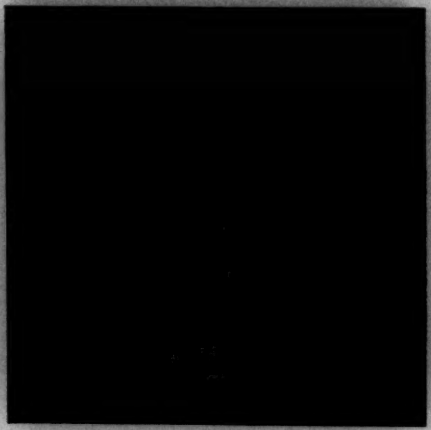


FIG. 10.

ever the necessity arises to change one or more insulators; but on the other hand, the mechanical resistance is undoubtedly much higher. In fact, in a cemented insulator the pressure between pin and porcelain is equally distributed over a large surface; while with the threaded-pin system, a slight bending causes the insulator to break, as it will in this case press against one point of the pin. The author has often tested insulators cemented on 1.5-inch rods, and always succeeded in bending the rods without breaking the porcelain.

When the span exceeds a certain length, care must be taken that the wires do not come in contact through their oscillation due to the wind. It is obvious that in order to avoid such a contingency, it is necessary that two or more wires should never be placed on the same level, and the adoption of cross-arms as practised in America is not to be followed. In any case, it is easy to calculate the deflection of the wires from their vertical position, due to the force of the strongest wind prevailing in the country and midway of the span, thus finding the distance between the insulators to prevent the wires coming in contact.

In the cases represented by Figs. 4 and 6 another solution is adopted: a line of six wires is divided into two sets of three wires each, one set on each side of the support and placed at a different height. Calculation shows that, if the two sets were placed at the same height, the wires would come in contact.

Fig. 7 shows a view of a line constructed following the aforesaid principles.

One may ask if it is worth while to make such a careful calculation. That is easy to answer: in order to reach a high economy in the use of iron poles, it is necessary to put in them only the quantity of iron that is absolutely necessary; and this cannot be done without a close calculation of every element of the line. The author had the opportunity of calculating the poles of a line built without much precaution, and found that each pole weighed about 200 pounds more than was necessary. As the number of poles was 600, the extra weight represented a total of about 60 tons of metal in excess of what was actually necessary.

The problem of high-pressure insulation is very carefully studied by European electricians. It is well known that glass insulators are not used in Europe and the reason for this, I believe, is that good porcelain can readily be obtained here. Glass is considered to have a better dielectric strength, but not as good surface insulation; moreover, glass is weaker against meteorological agencies, the superiority of porcelain being due to the materials composing the glazing. It must be said at once that European engineers do not consider American porcelain as good as European porcelain. It is possible that they may be mistaken, but a few tests made by the author on American insulators showed a higher dielectric resistance for the European porcelain which in appearance, finish and homogeneity of material is much better. Perhaps the difference in these particulars may have had much to do with forming his opinion.

In this connection I might mention that it is the general practice to examine all insulators on their arrival from the factory and put aside such as present a bad appearance; viz., such as are not glazed all over the surface, or that have cracks, spots, etc. This examination is performed by an ordinary workman specially trained and the pieces set aside are subjected to particularly severe tests. A few hundred insulators of American manufacture came over to be tested, and they were put through the usual examination. When the inspector came around, he found that all his American insulators were put to one side for surface faults. It must be said, however, that these insulators stood all the tests quite well.

The fact is that in Europe insulators may be obtained quite perfectly finished. It is considered necessary that the head and all external parts should be thoroughly glazed; to insure this they are supported from the bottom in the baking process. Another advantage in favor of European insulators is that the factories are willing to make any shape desired, which facilitates the introduction of new types.

In designing an insulator the following points are to be considered: dielectric resistance; resistance against surface-arcing; mechanical strength; facility of cleaning; ease of construction.

The first two points have reference to electric qualities and an ideal insulator ought to be so proportioned that, under a certain voltage, it should break in both ways, by puncture and by surface-arcing. It is well known how the resistance against puncture can be increased, by making the insulators of several pieces, introduced one piece inside the other. In general, the different pieces are cemented together with a kind of glazing in the process of manufacture and put on the market as single pieces.

The author does not follow this practice but prefers having them furnished by the factory in separate pieces, for the following reason: when the thickness of the porcelain reaches a certain limit, the ordinary testing will not puncture a sound insulator. In testing an insulator made up of two or more pieces, one layer of porcelain may be cracked but is protected by the other layers. When the tests are performed on the single composing parts, this cannot happen, and one is sure to have the insulators made up of sound parts. Moreover, each composing part can be better inspected and the character of glazing observed. Following this suggestion many factories produce insulators in two parts, which after test are put together with glycerine and litharge cement.

Experience has demonstrated that it is useless to increase the number of component parts; up to 40 000 volts two parts are quite sufficient and above that voltage not more than three are necessary.

The ability of an insulator to resist surface-arcing is due to its dimensions and shape, the latter to be considered under a double aspect: 1. The protective action against moisture and rain; 2 The property of giving origin to electrostatic phenomena. An insulator with a very large petticoat on the top and only a second petticoat round the pin will not afford a

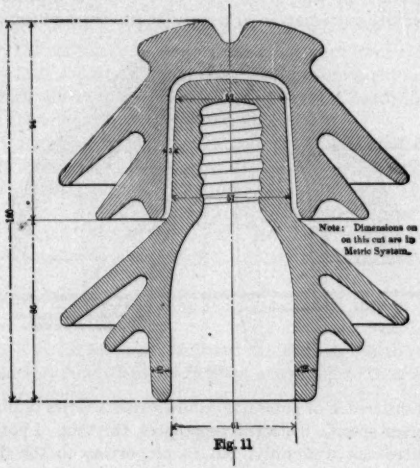


Fig. 11

very good protection against rain and moisture, as during a storm the inner petticoat will get quite wet. It is therefore good practice to have one or two intermediate petticoats, which will also ensure the dryness of some part of the surface in all kinds of weather. Care must however be taken not to put on too many of them, as their edges would come too near, thus forming a good path for the arc, besides increasing the difficulty of cleaning the insulator.

With reference to the influence of electrostatic phenomena on surface-arcing it is only possible to venture some assumptions, although it appears that they have a certain basis of fact. It is well known to those who have studied tests on insulators, that the surface-arcing does not always occur at once, but seems to be preceded by a number of static discharges between the petticoats. These discharges, of a bluish color, are very marked with insulators having petticoats close together, in which arcing seems also to occur with larger air spaces. It is not improbable that these blue discharges may produce an ionization of the air and moisture, which facilitates the striking of the arc.

This would appear to be unfavorable to the introduction of intermediate petticoats, and it may be further pointed out that

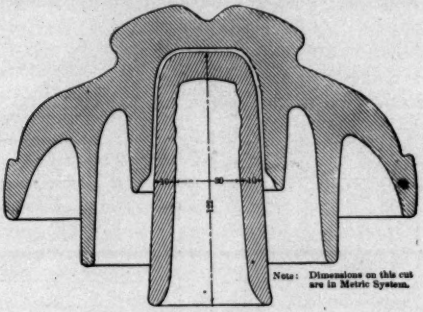


Fig. 19

when a difference of potential occurs across a series of dielectrics of different specific dielectric resistances, the drop of potential is distributed not uniformly, but in proportion to the dielectric resistances. Suppose then an air-gap so arranged that the drop of potential is 1000 volts per inch and that we introduce a porcelain diapraghm, the drop of potential per inch in the two resulting air-gaps may then be higher than 1000 volts per inch. Again, as it is desirable to have a low line-capacity, an insulator with a low capacity is to be preferred. Mr. F. Carcano has lately succeeded in comparing the capacity of different insulators by a very ingenious method.

He arranged a Wheatstone Bridge with two equal capacities, a and b, a variable capacity c, and the insulator to be measured,

of which we will call the capacity, x. In the place of the battery he connected a generator of electric oscillations, and in the place of the galvanometer a vacuum tube. When c is different from x the tube is bright, when by adjustment it is made equal to x, the tube is dark. By this method he was able to prove that the capacity of insulators of the various shapes used, vary from 1 to 1.9, a very large difference. The lowest capacity is shown by the insulators which have a few petticoats and one very open at the top, while the higher capacity is shown by those those which have two or more petticoats close together, and more so if the outer petticoat drops and surrounds the others.

From all these facts and considerations we arrive at the conclusion that the use of intermediate petticoats is to be limited to those strictly necessary to protect the inner part from rain and to ensure that a part of the surface shall be quite dry. Insulators which are supposed to meet the aforesaid conditions are shown in the annexed photo-prints and drawings.

The insulator shown in Figs. 8 and 11 is composed of two pieces and is used for voltages up to 30 000 volts. The petticoats are conical and have an inclination of about 45°. The two insulators shown in Figs. 9 and 10 are composed of three pieces and are intended for 40 000 volts. All these insulators have good mechanical strength, which is also an important consideration.

This paper which I have the honor to submit to you, shows one of the ways in which you may study a transmission line; it is a method which requires study and calculation, but the results are satisfactory, and lines constructed according to these principles are economical and, what is most important, safe in operation.

Discussion

(J. W. Lieb, Jr., read the paper, and in conclusion, showed a number of lantern slides embodying details of construction of Italian pole lines for power transmission.)

W. N. Smith:—It is to be regreted that the author of the paper is not present to describe in detail the practical operation of the construction shown. The author concludes his paper by saying that "the results were satisfactory," and that the lines were "economical" and "safe in operation." The methods outlined are so different from those in this country that it would seem very desirable to get in closer touch with the European engineers, and compare their results from operation with ours. A thorough discussion of details would tend to show clearly whether their methods are really an advance upon ours. The paper is an unusually valuable contribution to the cause of power transmission.

B. J. Arnold:—There is a transmission line nearly completed in Mexico, very similar to the construction described in the paper; it is one hundred miles long, built with steel towers of the regular windmill type, using from seven to twelve poles to the mile. This is supposed to be the most modern transmission line in existence.

The New York Central Railroad Company has decided that it is safer and more reliable to have its transmission lines overhead on steel poles than to place the wires in conduits; this decision is substantiated by information secured from different transmission lines in operation in this country. Every competent engineer who was consulted, advised the company to put the wires overhead if possible, because it is easy then to locate trouble promptly and to make repairs, while if wires are underground in conduits, it is difficult to locate trouble and difficult to make repairs.

L. L. Perry:—The type of European construction illustrated in Fig. 3 would seem to have been developed largely on account of the narrow streets requiring wires to be placed one above the other. This form of construction is a poor one for making intersections; a line of twenty or so wires so set would require a pole 50 or 60 feet high.

W. S. Dix:—A disadvantage of long horizontal spans is the possibility of adjacent wires touching; the vertical arrangement of the wires would obviate this trouble. American manufacturers of insulators are now following out the lines suggested by the author, and are reducing the number of petticoats, increasing the surface, and increasing the distance between petticoats,—thus reducing the arcing across. The insulators used at Shawinigan Falls have three petticoats, widely separated, and with these there has been no trouble.

W. N. Smith:—It is not clear from the figures that the three wires of a circuit are arranged at the points of an equilateral triangle. Do European engineers ignore the supposed advantage

of putting three conductors at the points of an equilateral triangle?

J. W. LIEB, JR.:—Several of the lines show clearly that a perfect equilateral triangular arrangement is intended.

C. F. SCOTT:—There has been a great difference between engineering work done inside of the power station and that done outside of the station. The development of electric apparatus has, in general, been in the hands of a few manufacturing companies with a corps of expert engineers, who have developed the machinery to a very high degree of perfection. In general it is thought that any one can run a pole line, and the engineering of it is left to the wireman. The outside construction has been haphazard; it has been handled by many local companies with little or no consideration for engineering requirements; some of these companies have done their work well, but, in general, external construction lacks standardization, uniformity, and fails to receive the higher grade of consideration that has been given to other departments of the work.

Mr. Semenza showed the speaker through the installation in Milan, and over the Paderno pole line; this line has the appearance of solidity and of being expensive, although the figures of cost given in the paper indicate that it is not unusually high. The substantial construction of the line and the respect which is shown to railroad crossings is a thing which impresses an American. The set of downwardly-projecting fingers about halfway up the poles renders the construction fool-proof as well as mechanically substantial.

(A vote of thanks was given to Professor Ryan and Mr Semenza for their papers.)

Discussion on "European Practice in the Construction and Operation of High-Pressure Transmission Lines and Insulators," at Pittsburg, March 10, 1904.

By N. J. Neall.

The speaker wishes to call attention to some points in the American practice of to-day.

Iron Poles.—The employment of iron poles for long-distance transmission lines would probably meet with considerable opposition in some cases where the freight and haulage charges are excessive.

A 60 000-volt, 100-mile transmission plant has recently been completed in Mexico, where No. 1 B. & S. gauge hard-drawn, 19-strand copper cables have been supported with porcelain insulators and iron pins by steel cross-arms on steel towers, there being usually 12 towers per mile, normal span 440 feet, although there are some spans of 1300 feet.

The speaker has never heard in American practice that transmission wires take up vibrations in opposite directions, and he believes that the possibility of line wires swinging together would be most remote. A line consisting of three wires in triangular formation swings in unison. On the other hand, it would seem that the construction shown in the paper might cause some difficulty from wires swinging together, and even more annoyance from a wire breaking and falling on a wire below it.

Another condition which appeals to the speaker is the increased vulnerability of the metal transmission-pole to lightning disturbances. It is a well known fact that in the Western United States lightning discharges often shatter wooden poles without impairing the service. Very often, in fact, the operators are not aware that such a circumstance has arisen until the patrolman discovers this fact on his rounds. If we are to follow a highly-insulated metal-line construction, the protective apparatus must be of the highest order to relieve this line of lightning and static discharges. The most common form of lightning arrester abroad is the horn-type, which depends for its operation on the attenuation and consequent breaking of the arc after a discharge over the arrester, which takes considerable time. American practice is represented by a spark-gap or gaps between the line and ground, equipped with resistances in such a way as to cut down the short-circuiting current following a lightning discharge, and so complete the cycle of operation in a very short time. There is at present a tendency in California to try the horn-type arrester on a very large scale, but so far data concerning the worth of this type are wanting and it cannot be considered as strictly representative. Both here and abroad the horn-type arresters for the higher pressures embody some form of series resistance

Insulators.—Both in this paper and the paper by Professor Ryan, we find the crux of the transmission situation to be the insulator. In all other points, generally speaking, high-pressure

operators to-day could, if it became necessary, increase the pressures were it not for the inability of the insulator to stand the increased pressure. It is not clear why the development of the high-pressure insulator has not progressed more rapidly. It may be due to the character of the materials which are considered proper for that device These are to-day, porcelain, glass, and possibly fibrous material. A common insulator to-day for higher pressure work weighs approximately 12 pounds, and some insulators in successful operation weigh as much as 50 pounds, the latter having stood a long-continued test of 120 000 volts.

It is questionable whether glass insulators can be used for very high pressures, especially if the line should be constructed with metal towers and pins. It is perhaps known that a high-pressure condenser having glass as a dielectric will show a peculiar frosting of the glass surfaces under strain which on close inspection will be shown to arise from a tearing off of glass particles by the static stresses. The same action would doubtless arise in pole-line construction, perhaps in a lesser degree; but inasmuch as the surface of the insulator is a factor in the insulation, this deterioration might have serious results.

MEETING AT CHICAGO, APRIL 26, 1904.

Discussion on "European Practice in the Construction and Operation of High-Pressure Transmission Lines and Insulators."

W. A. Blanck:—The comparative figures given by Mr. Semenza for the cost of wood and iron pole-line construction include an item for right-of-way. It is considered necessary here, for good practice, to secure a full right-of-way for the pole line, and not separate patches of ground for each pole, in order to enable easy access to the line for inspection. Generally speaking, highways are selected for transmission lines here so that easy access may be secured with the least expenditure for right-of-way.

The conditions for right-of-way are then the same for both wood and iron poles. The following table gives comparative prices for conditions here:

Wood Pole.

53 wooden poles, 35 ft. with cross-arms and pins, $6	$318.00
Erection, $1.20	63.60
3 by 53 insulators, $1.50	238.50
	$620.10

Iron Pole.

9 steel towers with cross-arms and pins, 45 ft., $60	$540.00
Assembling and erection, $7	63.00
3 by 9 insulators, $1.50	40.50
	$643.50

Discussion on "The Conductivity of the Atmosphere at High Voltages."

C. E. Freeman:—Professor Ryan's paper raises some very interesting questions in connection with high-pressure transmission systems, and all apparatus and materials pertaining thereto. There is a feature connected with the experiments upon which the deductions of the paper are based that is of especial interest. The speaker refers particularly to the method of measuring the voltage corresponding to the various conditions of brush discharge.

During the past year or so the speaker has had considerable experience in this, and has discovered, among other things, a most imposing array of difficulties. For example, in determining the sparking distance between needle points, it is very difficult to obtain consistent results; in fact with certain methods of operation it is practically impossible. If the needle points are fixed in position, and the pressure gradually raised until sparking occurs, data will be obtained which present decidedly irregular features due to the fact that even with the best regulation of pressure it is difficult

to prevent its being raised or lowered by successive steps. Furthermore, the time during which the potential difference is applied materially affects conditions, as it charges the atmosphere if the surrounding space is enclosed as it should be, and causes any foreign particles to produce conducting chains between the points, produces charges in the points themselves, etc.

The other method is to fix the pressure and then gradually reduce the gap until either the brush discharge or the spark, whichever one is sought, occurs. This latter method gives fairly consistent results. However, the character of the needle points imposes a most important operating condition. In order that this may remain constant it is necessary to change needles after each discharge, which, of course, results in different points being used for subsequent tests, the variation depending upon those which occur in the manufacture of commercial needles, which are most commonly used in this connection. Furthermore, the shape of the e.m.f. wave, having a given effective value, determines the breaking-down point of the dielectric under test. It is sometimes a question as to whether this shape is the same for the various conditions and operations under which the tests are being conducted, since the wave induced in the high-pressure winding is not necessarily the one operating at the terminals of the transformer.

The other method of measuring the pressure over the spark-gap is to assume the ratio of transformation, or determine it for some low value, and assume that it remains the same throughout the range of operation of the transformer. Such a method is wholly unreliable in nearly every case, since in transformers of this character the excessive insulation required results in very appreciable magnetic leakage in the transformer. Under such circumstances one of Professor Ryan's problems in electrical engineering due to the conductivity of the atmosphere manifests itself. For the higher pressures the inevitable brush discharge from the windings of the secondary causes the transformer to load up, and the ratio of transformation is by no means what it was under the unloaded condition which existed when the ratio was determined or assumed from the relation of the windings. We have at Armour Institute a 25-kw., 150 000-volt transformer of the core type. In order to test this feature the pressures of the primary and secondary coils were measured simultaneously. In order to do this something like 10 wattmeter multipliers were placed in series with a Weston voltmeter, and the combination connected across the high-pressure side of the transformer. Upon increasing the pressure of the transformer another of Professor Ryan's problems presented itself. At the higher pressures the brush discharge from the windings of the voltmeter so seriously disturbed its operation that at something like 10 000 volts potential difference of the high-

pressure side the indications of the instrument were practically useless. A Thompson voltmeter of the inclined-coil type was substituted and in this way this particular difficulty was removed. However, the result of the experiment showed that the ratio of the e.m.f. was by no means constant, nor did it follow any definite law, owing to the variation in those conditions which affect brush discharge.

A most important point emphasized by Professor Ryan is that of the relation of the dielectric strength of the air to the barometric pressure. From his most recent investigations it would appear that this strength approximates 160 000 volts per inch, at 200 pounds pressure. This is about four times the dielectric strength of ordinary transformer oil, as we have found it by tests in our laboratories. From this it would appear that Professor Ryan's suggestion that compressed air or carbon-dioxid would form a most desirable substitute for oil is a good one, provided means could be had for maintaining such a pressure. For large transformers there seems to be no reason why this might not be done.

Professor Ryan's paper contains many suggestions throughout, and constitutes a distinct and valuable step toward the final evolution of high-pressure apparatus and transmission systems in general.

A paper presented at the 185th Meeting of the American Institute of Electrical Engineers, New York, March 25, 1904.
Copyright 1904, by A. I. E. E.

THE RELATIVE FIRE-RISK OF OIL AND AIR-BLAST TRANSFORMERS.

BY E. W. RICE, JR.

Two types of transformers have been extensively used in electrical installations up to date, distinguished by the method of insulation and cooling employed. The "oil transformer" relies upon oil as the cooling and insulating fluid. The "air-blast transformer" contains insulation material mainly of cloth, paper, and wood impregnated with oil or varnish, and is cooled by the circulation of a blast of air. In both types the insulating material is of an inflammable nature, and under certain abnormal conditions may take fire with more or less serious consequences.

The electrical engineer must, therefore, consider carefully not only the relative but the actual fire-hazard which exists, and by proper and common-sense methods minimize such danger. Both types can be made entirely safe by correct methods of design and installation.

I think it will be admitted that in general that type which contains the greater quantity of inflammable material will occasion the greater fire-hazard. The inflammable material in an air-blast transformer of say 1000-kw. capacity will amount to about 800 lb.; in an oil-cooled transformer of the same capacity the amount will be about 7300 lb. While this comparison cannot be taken as a measure of the relative fire-risk, it is an indication to be considered, especially in view of the fluidity, the low temperature of ignition, and high calorific value of oil.

While the quantity of inflammable material in an air-blast transformer is, as stated, relatively small, it has an extended surface exposed to a large volume of air, and therefore, if a fire

starts from internal causes, such as short circuit or extreme overload, is capable of rapid combustion. This combustion could be checked by shutting off the flow of air to a transformer by means of a diaphragm automatically closed by the melting of a fusible link, the fusible link so located as to be melted by the first contact with flame; a method similar to that employed for closing fire-doors in buildings.

An oil transformer properly cooled is probably not particularly subject to ignition of the oil from internal burn-outs or arcs. It is well known that oil is an excellent medium for the smothering of alternating arcs, and this principle is utilized in connection with oil-switches. The vapor above the oil, may however, be ignited by electrical discharges. Even in this case, while the quantity of combustible material is enormous, the surface exposed is relatively small. The principle fire-hazard in an oil transformer is due to the large mass of inflammable liquid material which under certain conditions may become totally consumed. It becomes a special hazard in the case of fire from sources external to itself.

Considerations of first cost, economy of space, simplicity, operating costs, etc., have resulted in placing transformers in the same room with switchboards and other apparatus, such as synchronous converters, motor-generators, etc. Under such conditions, it would seem that the air-blast transformer constituted the lesser fire-risk than the oil transformer, and would therefore be generally employed if the fire-risk were the only consideration. The air-blast type, however, is limited in practice to pressures of about 30 000 to 35 000, as the static discharge which occurs at much higher pressures would in time break down the insulation. It is therefore necessary to employ oil insulation on the higher pressures now common.

The fire-risk can be practically eliminated by placing such transformers in a room or rooms separated by suitable fire walls from the other part of the plant. This plan has already been proposed and introduced. An entirely separate building, subdivided again into suitable rooms, may be employed where the maximum of safety is demanded. Much may be done to limit the risk, even when the transformers are placed in the same room with other apparatus, by proper systems of piping for draining the oil away from the building, by placing the transformers in a depressed area of concrete arranged for rapid drainage, etc. Of course any of the methods commonly employed for preventing,

limiting, or extinguishing oil fires may properly be employed.

In closing I wish to state that I consider a discussion of this subject both timely and important. It is well for engineers to consider carefully the dangers of all kinds, both to life and to property, that may exist in connection with the use of electrical appliances. The art is not advanced by ignoring or belittling the existence of real difficulties, but rather by intelligently facing the problems which occur and seeking a proper solution. Electrical energy is capable of being produced, handled, and transmitted more safely than any other form of energy, and such dangers as exist usually can be foreseen and safe remedies can be applied. On the other hand, we must not exaggerate the danger of fire from the use of transformers of either the oil or air-blast type. I believe the fire-hazard is extremely small, and can be and is being reduced to a negligible quantity by the adoption of methods similar to those I have outlined here.

BLANK
PAGE

Discussion on "The Relative Fire-Risk of Oil- and Air-Blast Transformers."

F. A. C. Perrine:—As regards the question of the relative fire-risk of oil- and air-blast transformers, the speaker disagrees materially from the conclusions and from some of the premises that Mr. Rice has laid down. The experience of the Fire Underwriters and particularly the practice of Mutual Fire Insurance Companies shows that: "In general that type which contains the greater quantity of inflammable material will occasion the greater fire-hazard" is not generally admitted. On the contrary, the question which is most important is not of the quantity of inflammable material, but of its disposition. Modern mill construction is one which shows a very large quantity of inflammable material, but its disposition is such that the relative exposed surface is small, and this is the most important point. One question relating to the disposition of inflammable material is the presence of dust, not only in connection with the apparatus in question, but throughout the building. In the most important fires—of six or seven—the disastrous consequences have been due to the accumulation of dust. A small fire, where there is dust accumulated, will distribute that fire very widely. In consequence, it seems to me that the fusible link is a very poor protection against fire, because if flame occurs we have the consequent danger from dust. In one instance of a wooden shop a single flame shot out, followed along dust-covered wires, and set fire to all parts of the building, so that the operatives had barely time to escape, although there were doors at both ends and in the centre of the building. This shows the importance in all fire-risks of avoiding the first evidence of flame.

The writer also speaks of the protection that can be obtained by means of systems of piping for draining the oil away from the building and by placing the transformers in a depressed area of concrete arranged for rapid draining. In the speaker's experience there have been three very serious fires in which the transformers have suffered. In one case four 500-kw. transformers were installed on a wooden platform, each transformer containing 14 barrels of oil. The fire occurred by reason of a small arc at the failure of an unimportant low-pressure switch. The fire, by dust and varnish, was immediately conveyed to the woodwork supporting the switchboard and the transformers. When the woodwork burned away the transformers dumped over, the oil spread on the floor, and there was little left of the building or the transformers. A careful investigation was made at the time to ascertain whether the fire had been due at all to the transformers. Every foot of wire in the transformers was gone over by hand to find out whether there was the least evidence of an electric arc. Not only was there no evidence of arcing, but markings on the case were found indicating that so long as the transformers were in

place and the water circulated in the transformer coils, the oil had not even evaporated. There were markings on the cases which showed plainly the level of the oil, and the markings opposite the water-coils showed that the transformers had been sufficiently hot to char the oil opposite the coils inside the transformer, but not to evaporate any considerable quantity of the oil. In the second instance where transformers were involved, the fire was occasioned by reason of a severe short circuit, distributing a flame to the insulation of the wiring in the station and to certain woodwork supports of the switches and other apparatus. The transformers were standing on a smooth cement floor and were not disturbed. All combustible material in the entire plant was destroyed, but on account of the continuous circulation of water in the transformers during the entire fire the only combustibles in the building which did not burn were the oil-transformers, and to-day every coil in every transformer is in operation. The wires were led into the transformers through porcelain bushings, surrounded by wooden bushings simply for the mechanical protection of the porcelain. The wooden bushings were burned out, but the oil was not materially evaporated in the transformers. In one or two of the transformers about one quarter of the oil was evaporated and in these the transformer coils were covered with a black sediment, but on clearing this off the transformers were put into and are still in service, the coils not having been injured.

In another instance a short circuit occurring inside of a 500-kw. transformer, the station attendant maintained the short circuit until he could telephone to the superintendent and have him come to the station. For about 20 minutes black smoke was coming out through the insulation bushings on the case by reason of the actual fire and short circuit which was occurring under the oil in the transformers; there was no flame and no conflagration due to anything inside of the transformers. The oil was simply boiled away.

In a recent instance where a transformer house was destroyed by reason of an extensive wooden framework for wires above the transformers, the latter were also destroyed because the cases were made of thin metal soldered together, and the heat was great enough to unsolder the cases and spread the oil over the floor.

The conclusion to which the speaker arrived from these facts is that the safest transformer, as regards fire-risk, is the one in which the combustible material is so disposed as to present the least surface to fire, and that is the oil-filled transformer. As regards further protection, he believes it is an error to provide means for draining away the oil. On the contrary, for absolute safety the transformer should be installed in a cement pit which can be filled with water, but not above the level of the transformer, because if the water is flowed into the transformer the oil will run out and even oil on the surface of water will catch fire; but

if the transformers are installed in a pit, which can be filled with water from an outside source, the pit can be filled with water and automatically drained away without topping the transformer. The latter is so connected by pipes that no falling part of the building can destroy the water connection of the pipe-coils in the transformer. In this way there is secured the safest possible installation of the transformer. Furthermore in ordinary cases the pit arrangement is entirely unnecessary, if only the water connection be arranged outside of the building so that falling parts of the building cannot destroy the piping. A number of years ago at a meeting of the Pacific Coast Transmission Association, Mr. George P. Low, who is perhaps the best electrical insurance expert on the coast, called attention to the great danger in transformers which have thin cases and particularly those in which the cases are soldered together, because oil can be heated to the temperature which will melt solder without setting the oil on fire. Mr. Low recommended at that time to the insurance authorities that they prohibit the installation, where the building was insured, of a transformer in a case of thin metal, or where a part of a falling building could punch a hole in the metal of the soldered case, or where the soldered metal would melt. This is a wise position which he has taken, and as a consequence that transformer is safest against fire-risk which is an oil-filled transformer, water-cooled, and arranged so that the water can be kept in circulation no matter what happens to the building, and the case of the transformer is strong enough so that falling parts of the building will not puncture it. What the speaker refers to particularly is that when you have a fire which is not complete, and objects weighing 50 or 100 lb. may be falling, the case should be strong enough to withstand such impact and especially should be of such character and strong enough that the fire itself, from the outside, cannot, by melting the case or melting the solder, allow the oil to run out. With these provisions, the oil transformer is by far the safest transformer to install.

J. S. PECK:—The introduction to the discussion on this subject covers the matter in a brief but comprehensive manner, and the speaker is in substantial agreement with all of the statements made therein.

It has been the speaker's experience that the air-blast transformer is more much susceptible to damage by fire which may be caused by static discharges, arcs, bad contacts, etc., than is the oil-insulated transformer, but on account of the relatively small amount of combustible material in the former, and further as it is in solid and not in liquid form, it is possible to have such material entirely destroyed with comparatively little fire-risk to neighboring apparatus or buildings.

In the oil-insulated transformer there is a very much greater amount of combustible material, which, while less likely to take fire, increases the fire-risk to neighboring apparatus or buildings.

Under certain abnormal conditions, it is possible that the oil in a transformer may take fire, consequently it is essential that proper means be adopted for extinguishing the fire and for preventing damage to other apparatus.

There are two sources of danger from the use of oil in a transformer. First, the oil itself may take fire; secondly, a vapor is given off from hot oil, which when mixed with the proper proportion of air gives a highly explosive mixture. This may be ignited by a spark and cause serious damage to the apparatus, and even to the building in which it is contained. The first danger, that of ordinary burning, is fairly well understood: the oil being raised to a high temperature, takes fire, and so long as it can obtain a supply of oxygen, burns with an intense heat and gives off a very dense, black smoke.

The oil used in transformers has a comparatively high burning point (a fire-test of approximately 400° fahr.), and it is necessary that the oil be raised to this temperature before it can be ignited. On account of the large amount of oil in a transformer, it would be necessary to supply a great amount of heat and for some considerable length of time in order to raise the entire body of oil to the burning point,—a condition which rarely or never occurs. It is possible, however, to have local heating in the oil so that a very small portion of it may be raised to a dangerous temperature and this may then be ignited. This local burning, if not stopped, will gradually heat the neighboring portions and result in a general conflagration. Such local heating may be produced, for example, by an arc drawn just below the surface of the oil.

The nature of the second danger; that is, explosions, is not so generally understood. It has been found that with the best proportions of illuminating gas and air under atmospheric pressure the greatest pressure which can be obtained from an explosion is somewhat less than 100 lb. per square inch, and it is probable that with the best mixture of oil-vapor and air at atmospheric pressure, a force of more than 100 lb. per square inch cannot be obtained.

The speaker has made a number of tests on transformer cases with the view of determining the conditions under which combustion of the oil, and explosions of mixtures of oil-vapor and air may be obtained, also to determine the best methods of extinguishing the flames.

A sheet-iron case provided with a tight cover was used; the oil was brought to a burning temperature by means of an electric heater and then ignited by an arc at the surface of the oil. As long as the cover was removed from the case so that a fresh supply of air could be obtained, the oil would burn fiercely, giving off a dense, black smoke. Placing the cover on the case would almost instantly extinguish the flames. It was also found that a liquid chemical fire-extinguisher was very effective but did not act so quickly as the method of excluding the air.

As long as the oil was maintained at a temperature slightly above the fire-point no explosion was obtained, but when the oil was raised 30° to 50° above the fire-point, so that fumes were given off at a very rapid rate, it was possible to obtain an explosion which would lift the light sheet-iron cover several inches off the case. If it settled back over the case the flames would be immediately extinguished. This explosion could be obtained with almost every trial, but not unless the cover was first removed and a supply of air permitted to mix with the oil-vapor. From the nature of these explosions it was evident that the pressure per square inch at the time of the explosion was very small. The test was of a qualitative instead of a quantitative nature, and no attempt was made to find definitely the exact pressure generated.

In this connection, another instance is worth citing. A transformer which had been removed from the oil, and therefore thoroughly oil-soaked, took fire from a torch used for unsoldering a connection. In a few seconds the insulation was burning fiercely; the transformer was quickly replaced in the tank of oil, and the flames were immediately extinguished.

From these tests it is apparent that if a transformer case can be made reasonably air-tight, combustion of the oil cannot continue. Where it is possible to use a riveted boiler-iron case with cast-iron cover, it may be constructed so that it will readily withstand a pressure of 100 lb. per square inch, and if it is properly vented a pressure above atmospheric cannot be obtained before the explosion unless vapor should be given off from the oil at such a rate that its escape is throttled by the vent-pipe, an almost impossible condition with a vent-pipe of suitable size. Even if vapor is given off at such an enormous rate, it seems likely that the supply of air would be driven out from the case, so that the mixture left would have little or no explosive force. Where this type of construction can be used, it seems desirable to make the case of sufficient strength to withstand an internal pressure of 100 lb. per square inch with a reasonable factor of safety, and to provide a vent-pipe of suitable size. In such a case oil cannot burn, and should an explosion occur it can do no harm.

Where a self-cooling sheet-iron case is used, it is impossible to make it sufficiently strong to withstand an internal pressure of 100 lb. per square inch, and for such construction it seems best to make the case practically air-tight so that oil cannot burn in it, and to provide a large safety-valve which will be lifted in case of an explosion and will then automatically close, thus extinguishing the flames.

It is well to consider carefully all dangers, no matter how remote they may be. How remote is the danger from the oil-insulated transformer is shown by the fact that, although there are several thousands of them operating to-day, many of an old type and often installed without apparent thought of the

fire-risk, it is probable that the number of cases of serious trouble resulting from oil fires may be counted upon the fingers of one hand, and in the majority of these cases the trouble has started outside the transformer. In fact, the speaker knows of but one instance where the transformer was directly responsible for the trouble. This was the recent fire at Snoqualmie Falls, Washington, and as it bears directly on the matter under discussion, the following facts will be of interest:

The water-wheels and generators at Snoqualmie are located in a pit about 250 feet below the top of the falls. The raising transformers are located in a building at the top of the pit. There were twelve 550-kw. self-cooling transformers located in the same room.

The first indication of trouble was the melting of the insulation from the conductors leading to the transformers. When an attendant reached the transformer house one transformer was found to be on fire; this was extinguished by means of a Babcock extinguisher. It was then discovered that another transformer was on fire, but as the contents of the extinguisher had been exhausted and as there were no other means of extinguishing the flames, they soon burned through the wooden top covering the case, then melted the solder in the side of the case, thus permitting the burning oil to flow out upon the floor. The burning oil melted the solder in the seams of the other cases and permitted the additional oil to flow out. The conduits for the low-tension leads acted as a drain and carried the burning oil down into the wheel-pit, and for a time the whole plant was threatened with destruction. Fortunately the flames were extinguished without other loss than the transformer house, part of the transformers, and the low-pressure cables. This trouble at Snoqualmie Falls, taken in connection with other information concerning oil transformers, leads to certain conclusions:

1. Where practicable, the transformers should be placed in a boiler-iron case, capable of withstanding an internal pressure of 100 lb. per square inch, the case to be suitably vented.

2. Where a sheet-iron construction is necessary, the case should be made practically air-tight and provided with a very large safety-valve, so that an internal explosion cannot burst the case.

3. Provision should be made for rapidly drawing off the oil in case it becomes necessary to do so.

4. Individual transformer units, or groups of units should be located in fire-proof compartments, such compartments to be suitably drained so that in case the oil escapes from the cases it can flow out where it can do no harm.

5. Adequate means should be provided for extinguishing fire, and the station attendants should be trained to know what to do in case of emergency.

With such reasonable precautions the fire-risk to other apparatus from oil-insulated transformers will be no greater than

from air-blast transformers; with either type the fire-risk is practically negligible.

Dr Perrine has referred to the fire-risk of transformers mounted in cases made of sheet-metal, having seams riveted and soldered, and has pointed out the greater safety of the water-cooled transformer mounted in a boiler-iron case with seams riveted and caulked. Unfortunately this latter construction cannot be used on cases for large transformers of the self-cooling type; and as there is and will continue to be a great demand for self-cooling transformers it will be necessary to take such precautions in the installation as will reduce to a minimum the fire-risk resulting from cases of this type. It is, of course, recognized that a self-cooling case made without rivets and solder is to be greatly desired. It is hoped that a case of such construction may at some time be devised.

CALVERT TOWNLEY:—Strongly emphasized the fact that neither type of transformer constitutes a serious fire-hazard. He stated that such fire hazard as does exist should be divided into two classes; first, a source internal; secondly, a source external to the transformers themselves. The papers and most of the previous discussion has had to do with the internal source of fires, but if transformers themselves constitute a low fire-hazard the internal source is of minor importance. The chief danger from internal fire is perhaps the blast of air in an air-cooled transformer, which may carry internal fire to adjacent apparatus or to inflammable parts of the building. It is sometimes but not always possible or easy to place transformers so that the exhaust air will impinge only on non-combustible materials. An automatic device for shutting off the air, which may not be operated for several years, is not likely to work when it is necessary.

For a fire external to transformers the air-blast type is more subject to attack:

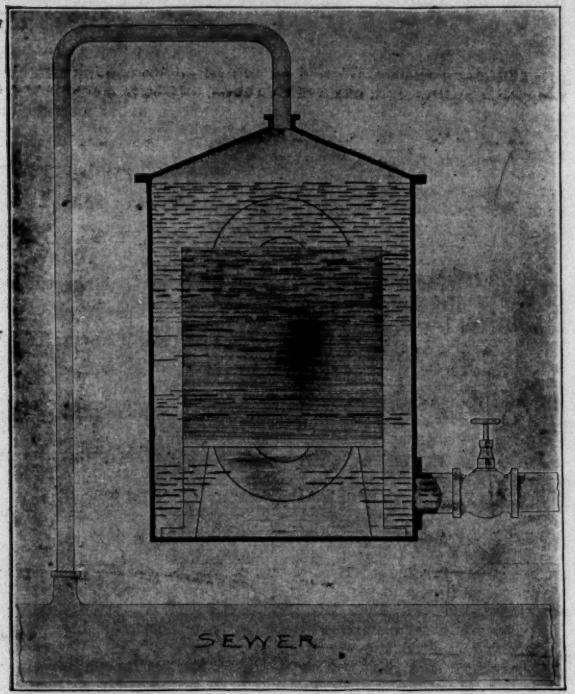
First, from flames, because it has no protecting case.

Secondly, from water, which, while it will not destroy, may put the transformer out of service for many days.

In a large installation, where both air-blast and oil-cooled transformers are installed in about equal capacities in the same transformer house, a somewhat severe fire occurred external to the transformers. The fire was extinguished after burning furiously for a time without damage to either type, but water completely soaked the air-blast transformers, which were out of service several days or until they became thoroughly dry, while the oil-cooled transformers were in use as soon as the connections could be re-established; that is, in a few hours.

Many people are misled as to the risk from oil-insulated transformers by the word "oil." That word suggests kerosene and the idea of very inflammable material, whereas oil of 400° fire test, such as is used for oil transformers, is far from an inflammable material at any but very high temperatures. A burning brand may be plunged into it and the fire will be extinguished.

Both types of transformer can be constructed and installed so that the fire-risk will be very small, and there is no reason why engineers or manufacturers should particularly favor the use of either type against the other.



RALPH D. MERSHON:—The speaker must differ from Mr. Townley in regard to one statement and that is that the fire-risk due to high pressures is greater than with lower pressures; if anything, the contrary is true. The speaker agrees with Dr. Perrine in regard to the relative fire-hazard, that it is not entirely de-

pendent on the amount of inflammable material, but is dependent more on the location and distribution of material. It also depends on the relative effectiveness of the provisions that can be taken for coping with fire. The scheme of installing oil transformers in separate rooms is not the best practice. In the case of high-pressure transformers it involves complications in wiring which are not advisable to use. The speaker is in favor of bare wiring for high pressures, and the moment you put these transformers in separate rooms you get into trouble with the high-pressure wiring. If the rooms are to be a thorough protection against fire they must be in the nature of vaults, which makes the wiring still more difficult. If the transformers are surrounded with fire-walls in a building of ordinary construction, and a transformer gets on fire, the transformer goes, and the oil may get away from you by the melting of the case.

In the case of an emergency such as might call for getting rid of the oil in the transformers, it seems a dangerous proceeding to draw the oil out of the case, when drawn out of the bottom, because in so doing air must get in at the top and there is a chance of an explosion, and that chance becomes greater as more oil is taken out of the case. This question of protection against fire has been carefully considered in the case of oil transformers, with reference to a plant of 50 000 volts and over, where the ultimate installation will mean transformers containing a good many hundred gallons of oil. The different methods of protection against fire were carefully considered and the scheme shown in the diagram finally adopted. The transformer case is built so that it will stand the maximum pressure which an explosion would cause, and all leads brought out through stuffing-boxes which will stand that pressure. To the middle of the top of the tank is brought a pipe running to the sewer and at the bottom of the transformer case is brought a water-pipe which has two valves in series, and between the two valves a drip cock to avoid any possibility of water leaking into the transformer through a leaky valve; the idea being in case of a fire emergency the water will be turned into the bottom of the transformer and drive the oil out at the top. No fire-walls have been installed in that plant although there will probably be some such walls between groups of transformers as an additional protection. As a last resort such an arrangement is about as safe as anything that can be thought of. Another advantage of this arrangement is that it leaves the whole space between the transformer free for a high-pressure wire, which can preferably be a bare one.

C. E. SKINNER:—An element to be considered in the oil transformer is the quality of the oil itself. It is extremely important that an oil be selected which has a flash-test considerably above the temperature at which the transformer will run in normal operation, including overload. At the present time a mineral oil is almost always used and can be obtained

with a great range of flash-tests. One having a flash-test not greatly above the normal operating temperature of the transformer will begin to give off fumes before the flash-point is reached, and these being explosive when mixed with air form a source of danger. An oil should be selected which has a flash-point not lower than, say 175° cent. Such an oil, if properly made, will have practically no evaporation whatever at 100°cent., this being higher than will be found except under the most extreme conditions of temporary overload. Too high a flash-test oil is undesirable on account of the viscosity being so great that the power to carry heat from the transformer to the cooler case is greatly reduced, and on account of its being unpleasant to handle.

Oil as a body cannot be set on fire easily; in fact a torch held to the surface of a body of oil will not set it on fire until the oil itself has reached the flashing temperature, or slightly higher. It is well known in the operation of oil-switches that an arc may be drawn under the surface of the oil and no fire results. This is true even though the temperature of the oil is above the flashing-point when such an arc is drawn, as air is absolutely necessary to the continued combustion of the oil. It is also true that an oil fire may be smothered with comparatively little difficulty, provided the oil is not allowed to spread. It is therefore obvious that a well-constructed fire-proof case with a cover which can be made practically air-tight, placed in a fire-proof compartment with means for draining, as mentioned by Mr. Rice, will reduce the fire-risk of oil-insulated transformers to a minimum. The great advantages of oil in insulating and cooling make it inadvisable on account of fire-risk to attempt to discard oil-insulated transformers, but to provide the necessary precautions to reduce this risk to the smallest possible amount.

H. G. STOTT:—He thoroughly agrees with the view taken by Mr. Rice, that the fire-risk is absolutely proportional to the amount of inflammable material contained in a transformer. When the insurance inspector makes an inspection of the building upon which he is about to issue a policy, he does not merely look at the outside walls of the building but makes a most careful examination of the contents—and the rate depends greatly upon these contents—so that no matter what arguments may be used as to the method of quickly getting rid of the oil and preventing it from flowing out of the case, thus spreading the fire, it should be treated as an extra risk as compared to an air-cooled transformer. A number of instances of serious fires due to oil-cooled transformers have been mentioned to-night, but nothing whatsoever has been said of a fire due to an air-cooled transformer, and the speaker cannot recall ever having heard of such a case where damage was done externally to the transformer through fire communicated by it.

Referring to the general subject of fire-risks and efficiency

of apparatus, he desired to call attention to the importance of having skilled attendants in all power-plants and sub-stations. The difference in paying the men $2 00 a day or $3 00 a day is very small at the end of a year, but the skilled attendant at the higher price will invariably save many times the extra cost of his salary. It seems the height of folly to expend hundreds of thousands of dollars on the very best apparatus which can be bought and then, for the sake of saving a few hundred dollars a year, turn it over to be operated by men of no technical education or special training.

The very best automatic apparatus will soon become inoperative if not given the proper amount of skilled attention. In at least two cases mentioned to-night of fires by transformers due to melting of the solder on the cases, it is quite evident that had there been an attendant present with the requisite amount of knowledge the fire would certainly have been limited to the transformer which was in trouble, instead of destroying the whole station. When anything happens to electrical apparatus there is no time to telephone to any one for information as to what to do; the man on duty must be competent to take care of any emergency which may arise.

P. N. NUNN:—The fire-risk due to the oil transformer is not negligible. In a large, modern power-house filled with expensive apparatus the large amount of oil contained in a full equipment of oil transformers is a constant menace to the entire plant. This is shown by the present record of fires and by the average station record of accidents which might have caused fires. The risk to each transformer, due to accidents within itself, may not be serious, but the combined risk due to many such transformers is very serious, because it applies to the whole investment in the plant. While compelled for the present to use oil transformers, the conservative engineer, in designing high-pressure work, cannot afford to neglect or underestimate their danger, or fail to employ every reasonable precaution, even perhaps some extreme measures, for protection. On this account exception is taken to the spirit of some remarks made this evening. Their effect has been to discredit the importance of this risk, and the protective measures suggested.

Within a few years the Telluride Power Company has lost two complete sub-stations; and while the fires may not have originated in the transformers themselves, the loss suffered, of which the transformers were but a small part, was chiefly due to the oil. It is this danger, to which all surrounding apparatus is subjected by the oil transformer, which constitutes the chief argument against it in favor of the air-blast transformer.

It might be possible to use some highly insulating gas incapable of supporting combustion, which might be circulated, perhaps under pressure, through both transformer and cooling coil.

P. M. LINCOLN:—To start and sustain a fire two distinct ele-

ments are necessary; first, a combustible, and secondly, a supporter of combustion. Bearing this in mind, suppose we analyze the relative fire-risks of air-blast and oil-insulated transformers.

In the air-blast transformer we have present constantly and unavoidably both the essentials necessary to start and maintain a fire, the insulation of the transformer being the combustible and the cooling air the supporter of combustion. The only thing needful, therefore, to start a fire in the air-blast transformer is simply a sufficient amount of heat at any point. In this respect, however, the air-blast transformer does not differ from any other combustible structure, except that under normal conditions the supply of air is by forced draught.

On the other hand, when we come to examine the oil-insulated transformer we find a structure in which the combustible and the supporter of combustion are capable of being easily segregated by a fire-proof wall. Relative fire-risk is not simply a question of the relative amount of inflammable material as Mr. Rice intimates, but it must also involve the question of the probability of a fire being started. The oil transformer, although it contains a considerably larger amount of inflammable material, has the advantage of segregating this inflammable material so that it can be made almost impossible for a fire to start within the transformer, and can also be shielded from a fire outside of the transformer.

The speaker's only personal experience with a transformer fire has been with the air-blast type. This leads him to doubt the practicability of Mr. Rice's suggestion of a fusible link in connection with a damper to shut off the air. In the instance mentioned not only was it necessary to close the damper in the transformer but also to shut off the air and finally to turn the hose on the burning transformer.

In the speaker's opinion the greatest danger in the use of oil-insulated transformers comes from improper installation and consequent probability of the floor becoming oil-soaked. When properly installed, neither the air-blast nor the oil-insulated transformer involves a serious fire-hazard; but if compelled to choose between the two types the speaker would, for reasons set forth above, be inclined to choose the oil-insulated transformer.

C. L. DE MURALT:—He does not agree with Mr Rice that the greater quantity of combustible in the oil transformers necessarily makes it a greater fire-risk. Transformers as a whole are not by any means the greatest fire-risk in any central station. In Europe, at least in Switzerland and France, the air-blast transformer is considered a considerably higher fire-risk than the oil transformer, and possibly for the following reasons: when air-blast transformers are overloaded, the insulation gets very much heated, and it is just possible that it breaks down somewhere, and takes fire either through the arc or through the heating of the insulation. In the oil transformer the oil forms, so to speak, a sort

of safety-valve, in that an overload will make itself felt only after a much longer time, when the other safety devices will probably have had time to come into play and cut the transformer out. This may be one of the reasons why air-cooled transformers in Europe are generally not used for sizes larger than about 150 kw. Oil transformers can be made almost fireproof, and it is a good plan to put them in separate buildings. This necessarily does not mean complication in the wiring. In the case of hydro-electric plants, which will mostly have to do with high pressures, the building is generally pretty long and narrow, with the units placed on one of the long sides. If the switchboard is placed in the centre of the other long side, it is easily possible to place the transformers in a room right back of that switchboard; similarly, if it is placed along one of the short sides; and in both cases the transformer room will probably not be much longer than the width of the main part of the central station. In both cases the leads from the generators will go to the switchboard, from the switchboard to the transformers, and as there need not be any switches in the high-pressure side of the transformers, they may go straight out. If the need for switches in the high-pressure side is felt, they can as well be placed in the transformer room and actuated mechanically from the switchboard. Thus, the line equipment will be, if anything, simpler than in the arrangement with the transformers in the central station itself.

In looking at the design which Mr. Mershon shows to-night, it would appear that when there is a necessity for flooding the transformers in order to bring the oil out, there is evidently a large fire, and every reason to suppose that the roof will come down and possibly break the oil piping which connects the transformers with the sewer. If this takes place, there may be serious danger of the oil doing more damage than if it had remained in the case. If transformers are located in a separate building, as just described, and placed in strong cast-iron boxes, or else in casings made of boiler-iron, riveted and caulked, and strengthened by angle-irons, and if these cases are well covered by a tight-fitting cast-iron cover, there is absolutely no fire-risk, either from the inside or from the outside, and such a transformer installation may be called as fire-proof as a brick wall.

O. S. LYFORD, JR.:—Before this discussion is closed more emphasis should be laid on a point raised by Mr. Townley. The title of the paper on transformers has naturally led to a discussion which gives the impression that these transformers constitute a very serious fire-risk. The fact cannot be emphasized too strongly, that although transformers are fire-risks these are not risks which cannot be successfully coped with. The speaker does not agree with Mr. Nunn as to the seriousness of the risk of the oil. This transformer subject ought to be separated into three heads instead of two; namely, the oil-insulated, water-cooled transformer; the oil-insulated, air-cooled

transformer; and the air-blast transformer. That they are all good should be emphasized. There is, however, a place for each type, as is usually the case with a number of good things of a similar character. Where water is available for cooling purposes, there is little question that the oil-insulated, water-cooled transformer is the type to be used. Where water is not available, the choice lies between the other two; but there is a distinct field for each. For instance, in a small sub-station, as in the case of an interurban railroad, there may perhaps be a couple of 250-kw. synchronous converters and an equipment of from three to six transformers of moderate size. In such a case the blower equipment is an unnecessary nuisance and the oil-insulated, self-cooling type has the advantage. On the other hand, in a large sub-station, such as one of those on Manhattan Island, there may be 20 transformers or more, and there is a gain by placing the transformers close to the synchronous converters and consequently distributing them throughout the building. Moreover with such a number of transformers the blower equipment is relatively a simple proposition, and all things considered, the advantages are in favor of the air-blast type. Therefore it seems to the speaker that a type of transformer for each specific service should be selected, and having done so it is perfectly possible so to design the plant that the risk of fire is extremely remote. In this day and generation it is seldom that we cannot afford to make a fire-proof building; many things besides transformers justify this precaution. The advantage of a fire-proof building was clearly demonstrated at Baltimore when practically the only two buildings left intact were the new power-station and the sub-station of the electric company, which were fire-proof, the fire could not get into the buildings. An electric plant costs so much money that the percentage added to make the building fire-proof is extremely small. With the surroundings fire-proof and the transformers properly located, the risk, as before stated, is extremely remote.

[COMMUNICATED BY LETTER.]

HOWARD BAYNE:—Mr. Rice's paper refers briefly to the necessity of employing proper means of preventing or extinguishing oil fires. In this connection the writer suggests the consideration of the use of steam as a means of putting out such fires. When properly applied, this has been found by those experienced in the oil business to be the best method of extinguishing an oil fire, particularly when the fire is serious.

Proper arrangements should be carefully planned and must be permanently installed. The transformers should be placed in a separate vault and in case of a large number they might be distributed among several vaults. Suppose each vault was equipped with one or more permanent two-inch steam lines, according to the amount of space in the vault. In case of fire, all outlets, such as doors and ventilators, should be closed and

the steam turned on. Both or either of these operations could be arranged to work automatically. The fire would be smothered in a very few minutes or possibly in less than a minute. The prime requisite is to have a large volume of steam turned into the vault quickly. If the fire is confined to the surface of the oil and the core and windings remain covered with oil, the transformer could be used again with very little, if any, delay.

The efficiency of steam in fighting oil fires is surprising. To illustrate: the company which the writer represents owned an large earthen storage tank at Gladys, Texas. It covered five acres and contained 200 000 bbl. of crude oil which was most inflammable since it gave off naptha vapors and hydrogen sulphide. On August 11, 1903, lightning struck the point of the conical roof. The small hatch at the apex was blown off and a tremendous blaze started. After several minutes the men got the hatch on again and turned steam into the tank. The blaze grew perceptibly less almost immediately, diminished rapidly, and finally went out.

The writer mentions this incident to show what can be done by smothering an oil fire with steam in a case where the fire has most favorable conditions for persisting. Compared to these conditions, those existing when oil in transformers catches fire would render the fire easy to extinguish. With oil-cooled transformers in "fire smothering" vaults the writer thinks the fire-risk would be almost nothing.

[COMMUNICATED BY LETTER.]

W. L. WATERS:—The question of the relative fire-risk of oil-cooled and air-blast transformers can be best decided by considering the different cases of transformers in stations with attendants, and transformers in stations without attendants. And also by considering fires due to internal causes and fires due to external causes.

Considering first fires due to internal causes. In an oil-cooled transformer it is almost impossible to start a fire due to a short circuit or a burn-out in the transformer itself, unless there is nearly unlimited power back of the short circuit. The oil will smother the fire so effectually that usually the mains will go before the transformer catches fire.

On the other hand, in an air-blast transformer a short circuit will turn the interior of the transformer into a blazing furnace, and even though the air supply is automatically cut off the transformer will certainly be totally destroyed unless it is cut out of the circuit. Whether the burning of the transformer itself starts a general fire depends, of course, on the arrangement of the building. If there are attendants present they can take care of the burn-out and can cut out the transformers before the situation gets serious

In the case of an ordinary fire due to external causes the oil-cooled transformer will be completely protected from damage

by the oil, as the latter will not be heated to ignition point and will prevent the heat from reaching the transformer itself. An air-blast transformer in a similar case would probably be ruined, though it might not add much fuel to the conflagration.

In the case of a large fire, the oil in an oil-cooled transformer would be ignited, and on account of the large quantity of inflammable material the results would be disastrous. This might be prevented if attendants were present to draw off the oil, or if automatic arrangements were employed for draining the oil in case of fire. But, in any case an oil-cooled transformer is a very serious risk in a large fire.

Speaking generally, then, an air-blast transformer is at the mercy of almost every fire, no matter how started; and though a single transformer may not add much to the conflagration it will almost always be seriously damaged itself. On the other hand, an oil-cooled transformer is in practically no danger except in a large fire, and then the risk is serious. Generally a set of oil-insulated transformers will be a much safer installation than a corresponding set of air-blast transformers.

[COMMUNICATED BY LETTER.]

IRVING A. TAYLOR:—It appears to be generally conceded that oil transformers are a greater fire-hazard than the air-blast type. Fire is not liable to start inside them, but in the case of an external fire the oil is liable to catch and produce a very hot fire. Internal short circuits are not likely to start a blaze, provided they are well under the surface of the oil, but if the latter is low, or the design is such that the coils are normally near the surface, an arc is liable to reach the surface, produce gas, and so set the oil on fire. The oil level should therefore be well above the coils.

In transformers which are sealed air-tight, a short circuit is likely to set up a sufficient explosive force to blow the cover off or to crack the case, the oil either running out or being thrown out—possibly on fire. Covers should therefore not be air-tight, but should prevent a circulation of the air. One of the greatest dangers from oil transformers is the fact that they are likely to leak under ordinary or extraordinary conditions. In the first instance, surrounding floors, whether of wood or concrete, become impregnated with oil and are very dangerous in the event of fire. Where cases are made of sheet-iron, or jointed with lead, an external fire is likely to open up the seams and let the oil out, with disastrous effect. All cases should positively be made of substantial cast-iron, without joints if possible. Where leaded joints are necessary, the lead should not be depended upon for holding the case together, and the latter should be fairly oil-tight without the lead.

Where oil transformers are used in large quantities, they should, where possible, be installed in a thoroughly fire-proof building used exclusively for the purpose and isolated from other

buildings. They should not be placed in buildings like hotels, or in any room not thoroughly and heavily fireproofed.

It is sometimes desirable to install oil transformers where artificial cooling is not commercially feasible, or where water-cooling is more convenient than air-blast. Otherwise, where the pressure will permit, air-blast transformers are always cleaner in operation as well as safer, and their use is therefore more satisfactory.

Mr. Rice's proposal to use fusible links in air-blast transformers is highly practicable. They should be combined with air-tight dampers, and should be hooked in place so that the dampers may be worked periodically for inspection purposes. While such links would naturally be placed in the draught at the top of the transformer, it would seem that the dampers should be placed at the bottom so as to prevent burning material being dropped into the air chamber and in that way carried to the other transformers.

There should be no inflammable material, either in the path of the air-blast above the transformers or in the ducts, and the wiring should preferably be by lead cables enclosed in tile right up to the transformer. Where it is necessary to use rubber-covered wires at the cable heads in the ducts, they should be thoroughly fireproofed.

[COMMUNICATED BY LETTER.]

NORMAN T. WILCOX:—He believes that where properly installed, the fire-risk with oil transformers is not so great as many imagine. In two cases of fire started by lightning in the step-up transformers in the Canyon station of the Colorado Electric Power Co., he found that they were caused by an arc, which would not have occurred if the oil had been kept to its proper height in the transformer. There was some trouble in putting out the fire, especially on account of the gauze ventilators in the top of these transformers. In one case these spaces were blocked up with waste, which had been soaked in water, thereby choking off the air supply and smothering the flame. In the first case, the engineer of the station threw off the cover to the transformer, which resulted in a lively blaze. This was carried up the wires to the wooden framework almost directly over the transformers supporting the high-pressure circuit-breakers.

He would not use an air-blast transformer on high-pressure work if he could avoid it, as he believes that not only is the insulation better with oil, but the oil prevents the insulating material from baking, drying out, and cracking, and insures a longer life to the apparatus.

[COMMUNICATED BY LETTER.]

A. C. PRATT:—For maximum safety, oil-cooled transformers should be placed in a strong boiler-steel case, with the cover

well bolted on. The latter should have a relatively large flap opening to act as a safety-valve, so arranged that it will not of itself remain in the open position.

There seems to be no doubt that inflammable and explosive mixtures accumulate above the oil in transformers; but the self-closing cover will promptly smother any fire which might be started from this cause. These gaseous mixtures seem to be formed, at least in part, by minute brush discharges in the oil, which break up the mineral oil into light volatile constituents and heavy asphalt-like residue. These effects may be readily produced experimentally, even at pressures below 10 000 volts.

There should also be a considerable air-space to allow for a possible boiling of the oil without boiling over. Such a transformer will most naturallly be of the water-cooled variety, and will always be mounted on a fire-proof foundation. Risk from external fire should be small. A large body of oil in a substantial case, with relatively small exposed surface, will pass through a fire, such as would make scrap of an air-cooled transformer, and be ready for service in a day or two, upon renewal of leads and bushings. Incidentally the transformer cover should be water-proof to such an extent that water from a hose will not fall into the hot oil. As a final precaution, arrangements should be made to drain spilled oil away from the building.

[COMMUNICATED BY LETTER.]

H. A. LARDNER:—In the discussion as to the relative fire-risk of oil- and air-blast transformers, the opinion developed that large oil-cooled transformers in boiler-iron cases with suitable covers and vents were practically fire-proof, provided they could be suitably protected from intense heat from the outside. A suggestion was made that this class of transformers be installed in a pit which could be flooded to within a few inches of the top. While this gives the needed protection, it is an extremely inconvenient method of installation, owing to the necessity of occasionally moving the transformers. On account of the high-pressure connections overhead it is usually undesirable to have a crane in the transformer room, and the most common method is to mount the transformer on trucks so that they can be drawn out of their position and under a suitable lifting device in another part of the transformer house when repairs are necessary.

Naturally the installation of transformers in a pit will necessitate the use of a crane and is therefore objectionable. It occurs to the writer that, as transformers are usually arranged along one side of a room, they might be mounted on trucks as usual and a comparatively light boiler-iron tank installed around them. The back and possibly the two ends would be supported by the walls of the building while the front could easily be held in place by tie-rods. The tank should be provided with an overflow of ample capacity to prevent the water reaching

the leads, bushings, or running into the transformer case. The front of this tank should be made in sections so that a section could be removed and a transformer wheeled out to the repair room when desirable.

It would not be a serious fault if this tank were not entirely water-tight, as water would only be turned into it during a fire, and some leaking would not be objectionable.

The method of protecting transformers by submerging them in cooling water is believed to be good, as there can be no objection to turning water into the tank immediately upon an alarm of fire and the protection need not be left until a last resort. It also seems to be well established that, if the attendants will promptly disconnect a transformer on fire from internal causes and cooling water be applied externally to a suitable air-tight case, the internal fire will generally extinguish itself.

[COMMUNICATED BY LETTER.]

H. F. PARSHALL:—The experience gained in England would indicate that there is no great risk from either type of transformer so long as it is intelligently installed. It has been pretty fairly proved that the oil transformer is more reliable over a wide range of conditions. The principal advantage of the air transformer is in installations like the Central London Railway where an accident to an air transformer brings no risk to the working staff, whereas an accident to an oil transformer might bring about serious consequences. Where, however, the transformers can be installed so that no matter what the occurrence there is no danger to life, the oil transformer is, in the writer's judgment, to be preferred

[COMMUNICATED BY LETTER.]

R. S. KELSCH:—As regards the relative danger or risk in the use of oil- and air-blast transformers, the writer considers the use of oil transformers extremely dangerous, unless they are installed in isolated buildings. And even then, he would hesitate a long time before being responsible for the installation of several banks of transformers, with each transformer containing from five to thirty barrels of oil.

The writer has as yet been unable to obtain an oil transformer where the case was oil-tight, notwithstanding the fact that the contract specifically stated that in order to be accepted it must be oil-tight. The writer has visited many plants and has not seen an oil transformer that was free from leakage. As a rule, a large drip-pan was placed under the transformers, to catch the leaking oil.

In one instance three 70-kw. transformers for supplying power to induction motors were installed in a building, and during a thunder storm at 2 a.m. one of the transformers failed. After the fire the evidence showed that a short circuit had occurred at a point near the top of the transformer coils, burning a large

hole in one of the cases and allowing the oil to escape, catch on fire, and destroy all three transformers as well as the building.

In another instance, a plant in Montreal was supplied with 5000-volt, three-phase power from a water-power plant. There were three 150-kw. transformers for reducing the pressure to 2000 volts. The building and contents were of a temporary nature. A short circuit ignited the oil that had previously leaked from these transformer cases, and that which had been forced out of the cases by the heat and the entrance of water into the transformers. The entire contents of the building were destroyed, only the walls remaining standing. In this same building, having wooden floors and temporary switchboards, an air-blast transformer of 250-kw. connected solid to the bus-bars, fed by eight 750-kw. generators was completely destroyed. It burned for fully four minutes before the current was cut off, but did no damage outside of the transformer itself.

In another instance in Montreal, two 2000-kw. 25 000-volt, air-blast transformers failed. There were no automatic switches and in order to get the current off it was necessary to telephone the power-house to shut down. This required nearly two minutes, which would be time enough to burn a hole through an iron tank filled with oil and allow the oil, already ignited, to run over the floor; but in the case of these 2000-kw., air-blast transformers, there was absolutely no damage, except to the transformer itself.

From his experience with both types of large capacity, the writer would not use oil-filled transformers, unless compelled to do so. He does not imply, however, that an air-blast transformer in a frame building with a 12-ft. ceiling would be considered safe, but in making the comparison, he refers to the installation of transformers of large capacities in a modern fire-proof station. The danger in one case arising from the possibility of the flames due to the air-blast reaching inflammable material, as against oil escaping from the tank becoming ignited and covering the floor of the station with a sheet of fire. While the oil used in transformers does not ignite readily, and will permit a red-hot iron to be plunged into it without danger, a heavy short circuit will ignite the oil, and in these circumstances becomes a dangerous piece of apparatus.

The writer suggests that air-blast transformers be equipped with a positively air-tight damper to shut off the air. The damper generally furnished is practically useless in the event of the transformer failing, but he has had transformers equipped with dampers which were practically air-tight. The parts were, however, not rough castings, but consisted of a cast-iron frame with brass gates machined so as to make a perfect fit. They are operated by a key hung in a convenient place on the transformer. It may be argued that this introduces a possibility of damaging the transformer, but not to any greater degree than the use of a valve to let water into the transformer or to allow the oil to escape.

[COMMUNICATED BY LETTER.]

H. W. TOBEY:—Many engineers contend that air-blast transformers are the safer of the two types. The preference being due, the writer thinks, to two reasons: first, because the containing tanks of oil-insulated transformers have been made extremely light and constantly leak oil, and in case of fire will often open and allow the entire contents to escape; secondly, because of the use of a poor grade of oil. With substantial tanks and an oil having a high flashing-point, these two drawbacks are entirely removed.

The oil-insulated transformer is capable of withstanding severe and long-continued overloads without injury, while in the case of a short circuit within the winding it is entirely under oil and the arc will be extinguished before injuring more than a single coil. Leads coming from the various coils are always a source of danger unless carefully insulated and surrounded by oil.

Relatively to the ability of oil-insulated transformers to withstand fires due to external causes, the writer can instance an interesting experience of a large power company in the West. At the time of the accident, the transformer equipment consisted principally of a large number of 840-kw. units, all oil-insulated and water-cooled. These were arranged in groups of three each for stepping up from 2300 to 50 000 volts. A fire starting from some external cause spread to the transformer room where it burned for three-quarters of an hour. At the end of this time a pipe line above the power-plant was opened and the place was deluged with water for over eight hours. It would seem after treatment of this kind that little would be left of the transformers except scrap-iron and copper. On the contrary four transformers (which were somewhat beyond the hottest part of the fire) were put back into service without repairs. Others were dried out with current for a few hours and after being filled with new oil were also ready for service. There were only four which actually required repairing. On these the porcelain insulators had been entirely destroyed and the covers were badly cracked. The inside surface of the tanks, together with the coils and cores, were covered with a thick deposit of carbonized oil. A large amount of water had also gotten into the tanks.

The cores were taken down, the coils cleaned, and the outer layer of tape replaced with new. The parts were then reassembled and the transformers put back into service where they are still in successful operation. It is not difficult to imagine what would have become of this apparatus if it had not been immersed in oil.

This brings up an interesting question. Is it good practice, as many maintain, to empty oil-insulated transformers in case of fire?

[COMMUNICATED BY LETTER.]

WM. J. HAZARD:—In an oil-cooled transformer, seal the space above the oil as thoroughly as possible and provide an adjustable vent. Fill this air-space with some inert gas such as carbon dioxide, supplied by a gas generator which will automatically maintain a slight pressure, just sufficient to prevent the entrance of air to the case. The writer believes this would effectually prevent the ignition of the oil gases, and hence add to the safety of the apparatus. The extra complication and the cost of maintenance would be insignificant. The amount of gas necessary would of course depend on the rate of leakage.

[COMMUNICATED BY LETTER.]

E. P. ROBERTS:—In the matter of oil transformers, the practice of the firm with which the writer is connected has been for some time to place such transformers in a fire-proof room, believing that the fire-risk justified the slight additional expense. Our practice has been somewhat of an evolution. The Dayton & Northern power-house, designed in 1900, had a separate room built on the outside of the building and to one side of the generator room. This additional room was fire-proof construction with fire-door between same and the engine-room, with the floor on the same level as the latter. The one sub-station of this road had a fire-proof room built into the balance of the building, which consisted of a synchronous converter room, the fire-proof static transformer room, a storage-battery room, freight and passenger offices, and, above the latter, living rooms for the attendant. The floor of the static room was on the same level as the floor of the synchronous converter room.

In each static transformer room the high-pressure lightning arresters and switches were placed. Since then this has been modified, and for the Dayton & Muncie Traction Co., now under construction, the design is as follows:

For the power-house there is an addition to the building immediately in the rear of the switchboard. The addition has two floors and the whole is of fire-proof construction, using steel, brick, and concrete. The upper floor is on a level with the engine-floor level and herein are placed the high-pressure lightning arresters and switches, while there is a fire-proof door into the engine-room. The lower floor is below the level of the engine-room basement and has a fire-proof door from such basement. In this room are placed the static transformers. The floor is of concrete, with drains, and in case a transformer should catch fire and the oil escape, it will run into the drains and be smothered. But even if the drain should not take it off with sufficient rapidity, it could not run into any other room.

The additional cost of the building is slight, as, in any case, room must be provided for the transformers and high-pressure switches and arresters, and placing these immediately behind the board is convenient, and does not necessitate complication in wiring or in mechanism for controlling the switches.

The sub-stations, of which there are three, are two new buildings and one old one. The new buildings have fire-proof static-transformer rooms with wire towers; the floor is drained and is below the level of the other rooms, and a fire-proof door connects to the synchronous converter room.

The old building is a remodeled warehouse in the center of the town. The static transformers are placed in a fire-proof room in the basement and a tight brick shaft runs from this room to the third floor. The high-pressure wires entering the shaft through large tile ducts, which together with the shaft act as ventilators for the room in the basement, pass from the pole line down the shaft to the transformer room. Cold air is taken from an area way under the sidewalk.

The synchronous converters are placed on the first floor, on foundations extending into the basement and adjacent to the static room. The high-pressure lightning arresters and switches are placed in the static room, the switches being controlled from the switchboard in the synchronous converter room. This is not quite so convenient an arrangement for attention as the other sub-stations, but it is expected that it will prove satisfactory; it was necessitated by the local conditions and the decision of the engineers relative to placing the static transformers in independent fire-proof quarters.

[COMMUNICATED AFTER ADJOURNMENT]

W. S. MOODY:—Some of the gentlemen who have discussed Mr. Rice's paper seemed to have missed the real point which he brought out in this paper. He refers, not to the relative liability of fire orginating in the two types of transformers, nor even the question of relative damage which the transformer is likely to experience should fire develop in it, but the relative "fire-risk" of a *station* equipped with one or the other type of transformer. It is not necessary in considering this point to assume that one or the other type of transformer is inherently the safer or even that fire originates in the transformer at all. The simple question is, how much does the addition to a certain building of a certain small amount of inflammable material such as is contained in the air-blast transformers, increase the fire-risk on the building and contents as compared with the addition to the same building of transformers containing several hundred barrels of oil.

The question seems hardly to admit of discussion. The chances of a fire external to the transformer communicating itself to the interior is also slight. But granted a fire can originate somewhere and that it may set the insulating material on fire beyond control, then will not a few pounds of varnished wrappings constitute a perfectiy negligible risk as compared with many barrels of oil?

[For further discussion on this paper see pages 236 and 246.]

BLANK
PAGE

A paper presented at the 185th Meeting of the American Institute of Electrical Engineers, New York, March 25th, 1904.
Copyright 1904 by A. I. E. E.

THE USE OF GROUP-SWITCHES IN LARGE POWER-PLANTS.

BY L. B. STILLWELL.

In a number of large electric generating plants recently designed in America, the feeder circuits are divided into a plurality of groups, and a switch designated a "group-switch" is connected into the circuit between the main bus-bars and each group of feeders. Obviously, no switch should be added to an organization of switch gear already very complicated and expensive, unless practical usefulness fully justifies its adoption. As this subject has never been discussed by the INSTITUTE, the writer avails himself of the opportunity presented by the invitation of the Chairman of your Transmission Committee to introduce it.

In considering a subject such as this, accurate generalization is difficult if not impossible. Probably no one who knows what engineering means would affirm without qualification either that he approves the use of group-switches or that he does not approve their use. There are few hard and fast rules in engineering. If such matters as the use or non-use of group-switches could be settled once for all, and for all plants regardless of size, function, or attendant conditions, the purchasing agent would soon succeed the engineer, the pharmacist would take the place of the physician, and the capitalist investing his money in electric power development and use would have no occasion to seek among technical advisers for sound judgment resting upon broad experience, and exercised in full knowledge of the existing state of the art, as well as recognition of its general direction and

tendency. Instead of attempting a generalization, therefore, we may consider more profitably the arguments for and against the group-switch in the case of a typical plant, and then glance at some of the modifications of function and circumstance which in the case of other plants would affect our conclusions. The group-switch first appeared in the plant of the New York Street Railway Company at 96th Street, but as the writer had nothing whatever to do with the design of that plant, he selects for consideration the plant of the Manhattan Railway Company.

In this plant two complete sets of main bus-bars are used. Switches are provided by means of which each of these sets may be divided into two independent sets of bus-bars to each of which four alternators and four groups of feeders may be connected. Eight group-switches are provided, through each of which current is supplied to a set of auxiliary bus-bars, to which in turn the individual feeders are connected through their respective switches. One of the eight feeder-groups is used to supply power to auxiliaries in the power-house. The other seven groups supply power, respectively, to the seven sub-stations which receive power from this central source. All switches in the high-pressure alternating-current circuits are of the motor-operated oil type.

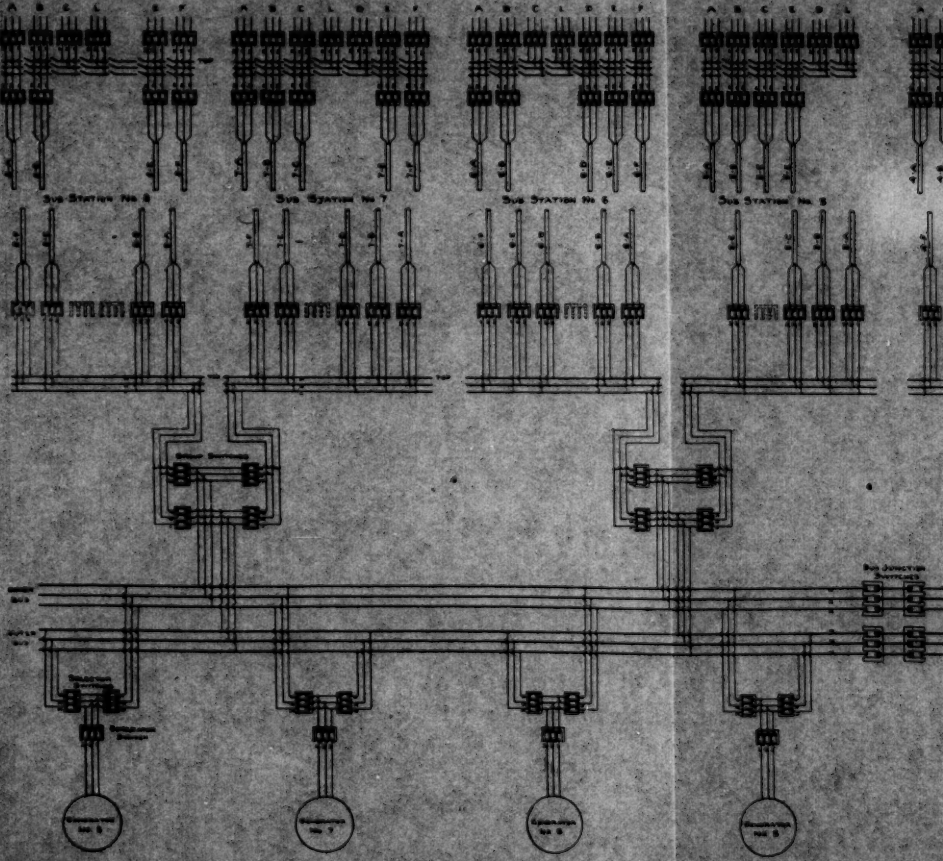
The arguments in favor of the group-switch as used in the plant of the Manhattan Railway Company are:

1—It affords an additional means of opening a feeder-switch that may fail to open its circuit, when operated for that purpose. The advantages of the group-switch in respect to this function to-day appear materially less than they did five years ago, for the reason that the power-operated oil-switch within the period named has demonstrated a high degree of reliability. However, it cannot be assumed that the feeder-switch is invariably reliable, and, therefore, judgment of the weight of the argument in favor of the group-switch, based upon its use as a reserve for the feeder-switch, becomes a question of judgment of the chances of failure of the feeder-switch on the one hand and the seriousness of total interruption of power supply on the other.

2—It affords means of reducing aggregate load upon the power-house in case of necessity, more rapidly and otherwise less objectionably than the usual method of cutting off individual feeders. It will sometimes happen in the operation of a power-plant that it becomes necessary suddenly to shut down one of the generating units. If the load carried at the time be such

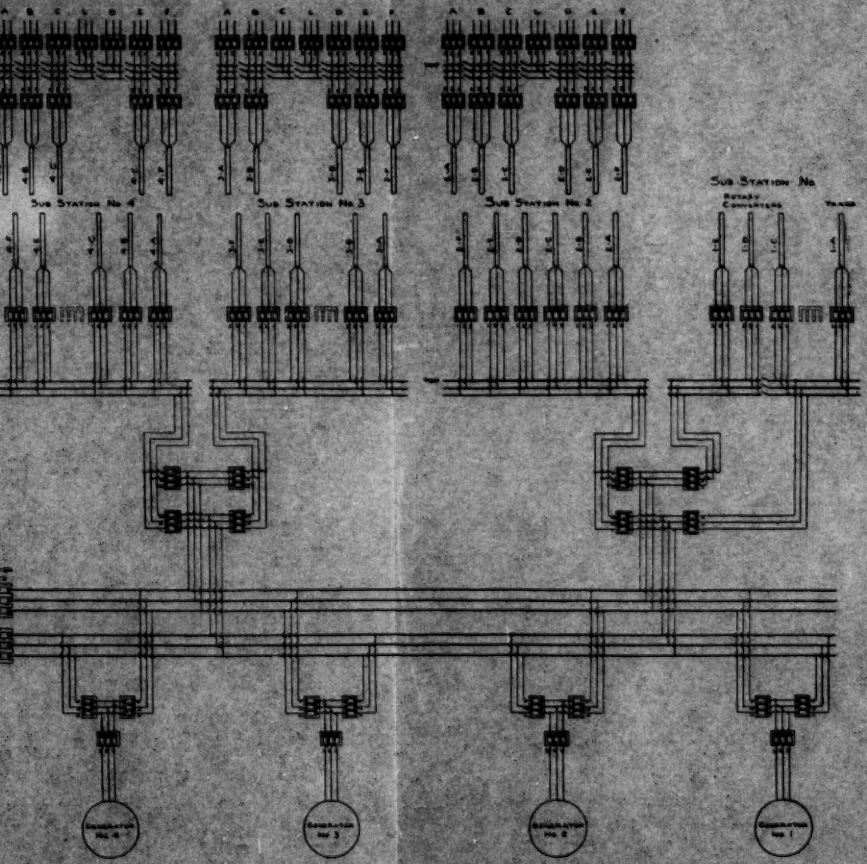
BUS-BARS, OIL-SWITCHES A

74TH STREET POWER STATION



AND A.C. FEEDERS

ON AND SUB-STATIONS



that the shutting down of the generator implies reduction of the external load, this can be accomplished most conveniently by operating one or two group-switches.

3—Where duplicate main bus-bars are used it facilitates transfer of load from one set to the other, in case it becomes necessary suddenly in operation to make such transfer. As bus-bars and connections are now installed in our best plants, this necessity does not arise frequently; nevertheless it is liable to occur, and obviously half a dozen group-switches may be used to effect the transfer in much less time than would be required were five or six times that number of individual feeder-switches used.

4—The grouping of the external feeder-circuits in group units bearing a simple fixed relation to the generator units establishes a symmetry and proportion most useful to the operator, particularly in times of emergency. In the case of the plant under consideration, at times of full load, the power passing through each group-switch is substantially equal to the output of one generating unit. This relation of course does not exist under partial loads, but under such loads it is not difficult usually to keep in service generating capacity exceeding the load by a margin sufficient to make it possible to shut down one generator without cutting off feeders; and in cases where this margin of capacity is not kept in service it is, nevertheless, a more speedy and certain operation to cut off the necessary number of groups of feeders than it would be to cut off a proportionate number of individual feeders.

The arguments against the group-switch are:

1—It introduces additional apparatus and, therefore, in itself increases the risk of interruption due to failure in switch insulation, etc. The successful operation of many plants, particularly in America, has been interfered with by the introduction of too much switch gear and too many safety devices, automatic and other; these additions in themselves being responsible in some cases for more trouble than they prevent; and it is to be noted that the group-switch implies the auxiliary bus-bar. Here again it is unwise to dogmatize, for as the result of additional experience the judgment of to-day may be reversed five years from now. As an expression of personal opinion, however, I may say that if the group-switch and the auxiliary bus-bars be reasonably well insulated and installed, the interruptions originating in this additional apparatus should be almost negligible in the case of such a plant as that which we are considering.

2—The group-switch and its bus-bars imply, of course, an increase in cost of the plant. In case of the Manhattan plant this increase is about 10% of the cost of the switch gear and measuring apparatus, and about four-tenths of one per cent of the cost of the plant. To put it another way, the cost of the group-switches and bus-bars for the plant approximates $20 000, and the annual cost, assuming this to be 10% of the investment cost, is $2000, which is about two-tenths of one per cent of the annual cost of operating the entire plant, including sub-stations.

In the plants in which the feeder unit equals or exceeds the dynamo unit of power, the group-switch, of course, disappears. In this case, however, it may still be advisable to use two feeder-switches in series in order to avoid the necessity of shutting down the entire plant in case of the failure of a single feeder-switch.

Obviously, also, there is no reason for attempting to use group-switches in cases where the total number of feeders is small.

For plants comparable in magnitude to the plant of the Manhattan Railway Company, using a very considerable number of feeders, the group-switch is important and its use generally advisable.

DISCUSSION ON THE USE OF GROUP-SWITCHES IN LARGE POWER-PLANTS.

ALEX DOW:—As to group-switches; the speaker considers that the separation of not only the feeders but generators into groups is now accepted as good practice. The drawing illustrating Mr. Stillwell's paper showed a condition normal in some plants but not representative of general practice. The accepted practice is, according to the speaker's observation, not to operate all the high-pressure generators in multiple but to separate the generators either individually or into groups and to give to each generator or group of generators its own group of feeders. The plant operated in multiple but only through the low-pressure distribution system—not on the high-pressure bus-bars; excepting, of course, that generators were put in multiple for the purpose of transferring load or taking machines in and out of circuit. The separation of generators and feeders into groups is indicated as advisable excepting where the transmission system has considerable resistance and inductance. A most notable exception which—like the tied-up air-switches—has also come recently under the speaker's observation is the Pacific Coast practice of running not merely several generators and feeders but several power-houses in multiple. The feeders and the tie-lines between power-houses are overhead and have high inductance, either natural or artificial. The frequency is high. Such a Pacific Coast system always "hangs on" to a short circuit. In one of these systems the established rule for dealing with a short circuit is to pull the field-switches of all synchronous apparatus—generators, synchronous converters, and motor-generators—excepting at one generating station. None of the apparatus is cut off from the system. The obvious result is that the remaining power-station has to supply a very large lagging current; the e.m.f. falls, and the short circuit breaks; whereupon the operators at the other power-stations and at the sub-stations re-excite the fields of their machines and normal conditions are re-established. A high-pressure system which can be dealt with in this manner has no occasion for group-switches. When, however, the conditions permit the concentration of a tremendous amount of energy on one fault, the group method is indicated and is already accepted as standard.

RALPH D. MERSHON:—The reasons given by Mr. Stillwell for the use of group-switches undoubtedly had great weight at the time the plants referred to were designed. That was when the oil-switch had not demonstrated its reliability, so thoroughly as it has now. In the present state of the art some of the reasons do not seem to stand very well. The oil-switches for pressures up to 10 000 which are constructed to-day seem at least as reliable, if not more so, than the apparatus which they control. If that is the case, it would seem that one is not justified in putting a number of switches in series. As regards the

case with which the load can be thrown off the power-house, that can be taken care of by having tripping arrangements which will operate a group of switches which can be tripped at once. As regards the transferring from one set of bus-bars to another, there is a great advantage for the group-switch if the transferrence must be made quickly. If time can be taken to do it, a selector-switch might be used instead of two oil-switches.

H. G. STOTT:—Referring to Mr. Stillwell's paper upon group-switches, the speaker considers the group-switch as a species of insurance. The more valuable the contents of a house, the more insurance a man wants upon it and its contents; and in the same way the more expensive a plant is and the more important the service supplied by it, the more important it becomes to take every possible insurance against a shut-down due to any cause, as a shut-down of no matter how short a duration has a most disastrous moral effect upon the entire business connected with it. As a matter of actual experience of more than two years with over 160 oil-switches, the speaker has never yet had a single case where they failed to open the circuit when required. In some short circuits over 100 000 kw. were concentrated, so that certainly they have had a severe enough test to prove their reliability under all conditions. However, it would require a great deal of courage to advise leaving out group-switches in plants above 35 000-kw. capacity of generating apparatus.

In regard to Mr. Dow's statement as to the operation of plants without generators being in multiple or upon groups of feeders, the speaker does not know of any plant of any size that is operated in this way. In all large plants in New York City with the exception of the New York Edison Co., everything is operated in multiple. He believes the New York Edison Co. operates its station in two sections, but in each of these sections several generators are operated in multiple.

LEWIS B. STILLWELL:—In the discussion, two things had particularly attracted the speaker's attention. One was the remarkable short circuit Mr. Scott developed when he endeavored to induce Mr. Nunn to open an air-switch; the other was the interesting and original design which Mr. Mershon had adopted in the important plant at Montreal. This design the speaker considered well worthy of careful study, although he had not definitely formed his opinion in respect to it; it impressed him as being a substantial addition to engineering practice in the matter of oil-insulated transformers.

So far as the subject of group-switches was concerned, he was glad to know that Mr. Stott, who is now in responsible charge of the operation of the Manhattan plant, agreed with him in believing their use to be advisable. Obviously, their use or non-use depended primarily upon the degree of importance attached to an interruption of service and there was one

way to state the case in respect to the particular plant to which he had referred in his introduction which was perhaps stronger than any which he had used; viz., by comparing the annual cost of the auxiliary group-switches and their bus-bars with the revenue earned by the system in a short interval of time. As he had stated in the introduction, the cost of the group-switches with bus-bars is not over $2000 a year, allowing 5% for interest and 5% for maintenance, while the gross receipts of the system in rush hours often exceeds $5000 an hour. When the subject is looked at in this way, it is evident that the additional precaution is well taken. The speaker did not agree with Mr. Mershon in regard to the use of group-switches. The speaker understood Mr. Mershon to say that if by using a single switch for each feeder the risk of interruption of service by reason of switch failure was reduced to a point where it did not exceed the risk of interruption due to failure of the apparatus controlled, it would be unwise to double the switches. The speaker felt that this view was not correct and pointed out, for example, that if in a given plant using no group-switches six interruptions of service should occur in the course of a period of five years by reason of dynamo failures and six interruptions by reason of switch failures, it would be wise to use group-switches which might be reasonably expected to reduce the interruptions due to switch failure and so reduce the total interruptions of service.

[COMMUNICATED BY LETTER.]

WILLIAM B. JACKSON:—In determining the best arrangement of the switching equipment for a power-plant, two prime considerations and one of lesser importance must be the deciding factors. These are in order of importance: the reliability of service that may be expected from the system under consideration; the convenience and flexibility of operation; and the cost and depreciation of the equipment.

The use of duplicate bus-bars throughout electric power-plants as well as two single-throw selector-switches for transferring from one set of bus-bars to the other in place of one double-throw switch, has come to be recognized as standard construction.

No single arrangement of switching devices can be laid down as the perfect one for all plants. In general, however, the most reliable service is attained by bringing directly to the main bus-bars all of the generator and feeder circuits. Each circuit in this case should be supplied with a master-switch by which it can be disconnected independently of its two selector-switches. With such an arrangement of circuits no local accident which may occur beyond the main bus-bars and their connections can interfere with more than one circuit. Also no switch need be of greater capacity than that of its circuit. As the quantity of energy which must be handled by a switch has much to do with the reliability of its operation, this latter consideration is of im-

portance; especially as the individual circuits of large power-plants usually transmit as much power as can be conveniently handled by one switch.

In a group-switch arrangement as described by Mr. Stillwell the reliability of service is not so great as in the arrangement above described, since it introduces auxiliary bus-bars and associated connections, an accident to which will disturb the operation of all of the circuits in the group; also by the addition of currents of several circuits at the group-switch a troublesome switching problem is engendered.

By carrying each of the circuits directly to the bus-bars a more convenient and flexible system of switching can be arranged. The individual circuit, which is the natural unit of distribution, is duly recognized in this arrangement. By this system each circuit, whether it be a generator circuit or feeder circuit, has its own individual group of switches the operation of which will effect its connections alone, and it may be connected to either or both sets of bus-bars or disconnected therefrom with complete independence.

Although more switches are required for a reliable system for individual circuit control, yet the fact that each switch has to do with its own circuit alone permits of a switching system of great simplicity, and of perfect flexibility. The controlling table and instrument board can be arranged so that each circuit may have its own individual sections upon which all controlling levers, or switches, and all indicating instruments may be arranged so that the exact condition of the circuit can be instantly seen, from the observation of a single section.

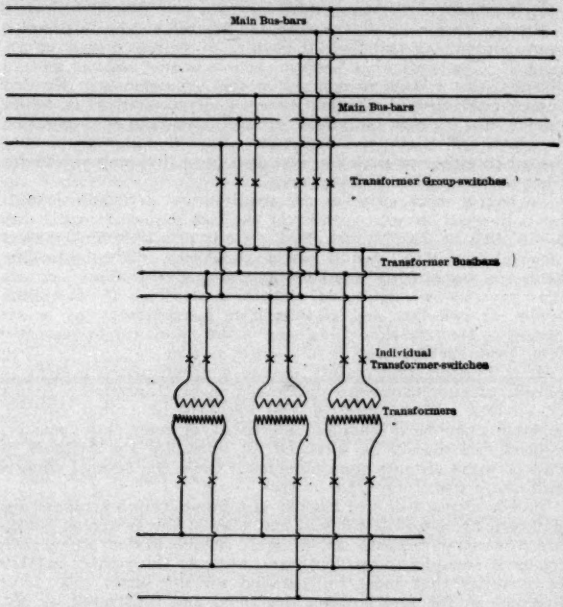
It is entirely unnecessary to use a group-switch system to permit of simultaneously disconnecting or transferring groups of circuits. With most of the methods of switch control, whether they be mechanical, electrical, or pneumatic, master-control can readily be arranged for operating the switches of two or more circuits simultaneously, while the several circuits still retain their individual control.

In the element of cost the use of a group-switch arrangement will usually reduce the actual first cost of the switching equipment as compared with a thoroughly reliable system where each feeder is brought to the bus-bars, owing to the greater number of switches that must be installed for the latter case. For instance in the arrangement described and illustrated by Mr. Stillwell, six circuits are handled by use of six single-throw circuit switches and two group-switches. To control six circuits where each circuit is brought to the bus-bars, twelve selector-switches and six master-switches would be used.

The matter of depreciation will also favor the group-switch arrangement owing to the less number of moving parts therein contained though this will not be so great as might be supposed, since it is necessary to introduce the higher-capacity switches in the group system as already referred to.

The cost of the switching devices required for any power-plant is exceedingly small as compared with the total cost of the plant, and a slight gain in reliability, ease and flexibility of operation will more than compensate for any added cost and depreciation that may be occasioned by the bringing of each circuit to the main bus-bars.

The plant referred to by Mr. Stillwell is an unusual case in which each set of feeders that are controlled by the group-



switches may apparently be considered, under ordinary circumstances, as a multiple-feeder carrying current to the same set of sub-station bus-bars. Under such conditions it would always be necessary to transfer all of these circuits simultaneously. It would seem that a more perfect result might be attained by arranging the system throughout so that all of these feeders would not of necessity be operated from the same set of main bus-bars.

In power-transmission plants, where step-up transformers are employed, a use of switches is made that may properly be considered in this discussion, but which is somewhat different from the group-switch arrangement described by Mr. Stillwell. In all plants where Δ-connected single-phase transformers are used it is desirable to be able to disconnect any one transformer without disturbing the others. Also, it is quite important that in changing from one set of bus-bars to another all of the transformers be transferred simultaneously. It is therefore quite desirable that the individual transformer circuits should be provided with their own disconnecting devices while transformer group-switches be arranged for transferring the Δ from one set of bus-bars to another. The arrangement is shown in the accompanying sketch.

Taking everything into consideration, it is the opinion of the writer that the arrangement of group-switches as described by Mr. Stillwell is one of limited usefulness, and that an arrangement wherein the individual circuits are brought directly to the main bus-bars is usually to be preferred.

[COMMUNICATED BY LETTER.]

IRVING A. TAYLOR:—Mr. Stillwell has enumerated, in very concise form, the several advantages in favor of group-switches. No. 1 is that they provide an additional means of breaking the circuit in case of failure in the feeder-switches. Nos. 2, 3, and 4 cover advantages of group operation.

It seems as though the latter class of advantages might be obtained as readily and more simply and cheaply by the use of multi-point control-switches, used in parallel with the ordinary ones; as group operation could be easily obtained in this way.

Advantage No. 1 was certainly very strong at the time the plants in question were designed, but, as Mr. Stillwell says, is not so important to-day, on account of the reliability of the oil-switch, but yet has some weight.

There are few plants, even of great magnitude, where a complete shut-down for five minutes (sufficient to clear a defective switch), once a year or two, is of sufficient importance to warrant the expenditure of several thousand dollars to prevent it. Probably large lighting companies, having a low-pressure network, are an exception to this, on account of the difficulty of starting up after a shut-down. With this exception, it looks very difficult to decide in favor of group-switching at this point of time, and this applies particularly, as inferred by Mr. Stillwell, as plants are smaller.

Another point that has to be considered in arranging feeder- or generator-switches is that few men of sound judgment would allow a man to touch lines, or even the coils of a generator, if an open oil-switch were the only thing between the man and death. The risk is not much; but life is too important to assume it. An oil-switch handle may be open, but one line may be

short-circuited in the switch, or the latter may be broken. Therefore, some kind of an air-switch should be provided in series with each feeder or generator oil-switch, for use on such occasions. An ordinary air-switch having short break, but provided with barriers, seems to be very proper for the generator circuit. On feeders, it seems as though a fuse-block could be used to advantage, as it will not cost materially more than the air-switches and will give additional means of automatically disconnecting the circuit, as well as fulfilling the above functions. In any case such switches or fuses should be installed between the bus-bars and the oil-switch.

Expulsion fuse-blocks with spring tension have proved to be very reliable on ordinary power and lighting circuits, provided they are occasionally inspected. It would be interesting to know whether such fuses are really reliable for breaking high currents to synchronous apparatus, as this is the worst possible condition. The writer understands that this fuse-block has not the same vital objection as the air-switch, in causing an abnormal rise of pressure or breaking the circuit. It may seem like a step backward to propose fuses, but if the objections noted are set aside, it would seem as if this were their proper field.

[COMMUNICATED BY LETTER.]

GILBERT WRIGHT:—The writer suggests that in place of the arrangement of group-switches, selector-switches, and bus-bars shown on the plan submitted by Mr. Stillwell, one set of main bus-bars be used instead of two, and that the feeders be tapped directly from this one set of bus-bars, the feeders to be controlled electrically, singly, and in groups. This method of control; that is, single and group, is very readily accomplished by installing one control-switch for each feeder and one master-switch for each group. This reduces the total number of switches by 32, eliminates one set of main bus-bars, eight sets of group bus-bars, with the necessary wiring between the switches and bus-bars.

Mr. Stillwell says that the group-switches and the group bus-bars in this station cost $20 000. Estimating the cost of the 16 selector-switches for the generators and the extra set of main bus-bars, with the necessary wiring, to cost another $20 000, would make a total saving of $40 000. By spending, say, $10 000 of this in improving the feeder-switches and in additional insulation and fireproofing of the main bus-bars and wiring, and on the additional control-wiring necessary to control the feeders singly and in groups, it is the writer's opinion that a greater factor of safety on the whole plant would result and that the same facility of handling changes in load would be obtained as by the plans described in Mr. Stillwell's paper.

The writer looks upon group-switches, duplicate bus-bars, and the necessarily complicated wiring for connecting same in the power-house, as so much insurance on the continuous opera-

tion of the plant; this insurance placed in small amounts, in a great many places and at a cost much too large in proportion to the results obtained. It will be seen that a possible saving of $30 000 could be made on this plant by the method described above.

The writer would suggest for general station practice to use as few switches, bus-bars, and as little wiring as possible, and make switches larger, more rugged, and with capacity to handle not once but many times the maximum load that they may under any conditions of service be called upon to handle.

[COMMUNICATED BY LETTER.]

JOHN B. TAYLOR:—The writer agrees entirely with the author of the paper, that no hard and fast rules can be laid down as to the conditions under which the use of the group-switch is, or is not, advisable. Apart from the question of mere additional cost, the following features in connection with the plant have some bearing on the matter:

(a) Pressure of the system.

(b) Number of cables or independent circuits supplying energy to each of the sub-stations.

(c) Liability of trouble occurring on any of the conductors or cables, requiring disconnection from the network.

(d) Reliability in operation of the high-pressure switching apparatus used, as shown by behavior of a number of switches in practical service.

(e) System of connection of low-pressure distribution; that is, with one sub-station out of service can cars be kept in operation adjacent to this sub-station, through power supplied by other sub-station?

(f) Character of service,—whether city work or interurban.

Taking up in order the various arguments given in the paper:

I. "Additional means of opening a feeder-switch that fails to open its circuit when operated for that purpose." The need of two switches in series for all circuits, both generators and feeders, connecting to the main bus-bars, must finally be largely a matter of personal opinion, based mainly on what the designer of a new system has observed or can learn from others regarding the behavior of the high-pressure switch it is proposed to use, under severe service conditions.

II. "It affords means of reducing aggregate load upon the power-house in case of necessity, more rapidly and otherwise less objectionably than the usual method of cutting off individual feeders." It is evidently advantageous to cut off all energy supply to a single sub-station without the necessity of locating and individually operating five or six controlling switches located at a greater or less distance from each other. While the use of the group-switch and the bus-bar gives the complete control of power supply to each sub-station through an individual switch, it should be noted that this same control could be obtained at

an expense extremely small, compared to the cost of a group-switch and additional bus-bar, by bringing to a central point the wires which control the opening of the feeder-switches. A single motion of a gang-switch would simultaneously open all of the four or five or more feeders supplying the sub-station to be cut out.

III. " Where duplicate main bus-bars are used, it facilitates transfer of load from one set to the other . . ." Obviously for the Manhattan station, fewer switches are necessary with the group bus-bar than would be required if two switches (one for each bus-bar) were supplied for each of the feeders. He thinks that in many plants the extra expense and complication of a duplicate bus is unnecessary and undesirable. In most cases, a single set of bus-bars, properly installed, with knife-blade disconnecting-switches, will be found cheaper, simpler, and quite as reliable. With very few exceptions, a spare bus-bar when installed is made use of only to allow men to work safely upon, or near, the regular bus-bar. The disconnecting-switches above referred to need occupy no additional space, and a judicious placing of same, to suit number of generators, number of feeders, character of load, etc., will permit cutting out a portion of the bus-bar, so that same may be handled with safety.

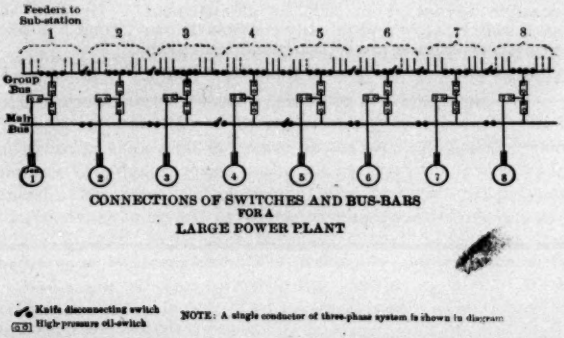
IV. " The grouping of the external feeder circuits in group units bearing a simple fixed relation to the generator units establishes a symmetry and proportion most useful to the operator, particularly in times of emergency." This symmetrical relation between number of generators and groups of feeders, is obviously not necessarily a general case, and while the proportion will hold more or less closely in most cases of city work, the relation between the number of generating units and outgoing feeders in a power-plant supplying an interurban system or a portion of a main trunk-line will be quite different. In the case of the city system, each sub-station is supplied by a number of independent cables, while in the general case of the interurban system or trunk-line, there are relatively very few feeders, which may supply several sub-stations, passing in and out of the stations intermediate between the generaing stations and the most distant sub-station. For service of this character, there could in many cases be but two groups, each consisting of the line either way from the power-plant. In the latter case, a group-switch is likely to be of very little benefit.

Regarding the two arguments cited by Mr. Stillwell against the use of the group-switch; that is, additional apparatus which may of itself increase the risk of interruption of service and the cost of installation and maintenance, the writer comments as follows:

The advantages to be gained through a complicated system of connections and switches equipped with all the various automatic and protective devices for overload and reversal in direction of energy transfer, with arrangements for instantaneous operation and adjustable time-limit, are always more plainly

evident on paper than in a plant in practical operation. It is better to err on the side of simplicity, giving the reduced amount of apparatus rigid inspection and attention, than to go to the other extreme of constructing a cumbersome switching arrangement, which is flexible only in theory, and confuses the operators in times of emergency by offering a number of possible combinations, each of which may be right, but no one of which is the only thing to be done, and that in a hurry.

Referring to the diagram of bus-bars and switches in the 74th Street station of the Manhattan Railway Company, it will be noted that each of the group bus-bars is fed at a single point and has no sectionalizing switches. Now this means that no work can be done on a group bus-bar without entirely shutting down a sub-station, and any trouble occurring on this bus-bar or on the connections between it and the switches, will cause a complete



CONNECTIONS OF SWITCHES AND BUS-BARS FOR A LARGE POWER PLANT

Knife disconnecting switch
High-pressure oil-switch

NOTE: A single conductor of three-phase system is shown in diagram

shut-down of a sub-station, until the trouble can be repaired or cleared. This criticism could easily be avoided by feeding the auxiliary bus-bar at the middle instead of at one end, and inserting knife-blade sectionalizing switches either side of the feeding point. Such an arrangement would permit the operation of the sub-station with half of the feeders, while work might be done on the other half of the group bus-bar. A still better arrangement would be to tap one of the group-switches at each end of the group bus-bar, knife disconnecting-switches being inserted in the middle of the group bus-bar.

In the accompanying sketch, the writer has drawn up an arrangement of switches and bus-bars which is essentially a single main bus-bar and a series of group bus-bars, which, however, may be interconnected to form a reserve main bus-bar in case of trouble or to facilitate work upon the main bus-bar. It will be noted that this

arrangement in its normal connection retains the group switch and also provides two switches in series between each generator and the bus-bar. The writer has shown the same number of generators and groups as are shown in the Manhattan diagram, and it will be noted that sixteen less high-pressure oil-switches are required. Oil-switches might be substituted for the knife-switches connecting the different group bus-bars and also in place of the knife sectionalizing-switches in the main bus-bar, but the writer considers the use of oil-switches at these points unnecessary.

[COMMUNICATED BY LETTER.]

H. F. PARSHALL:—So far as the writer is aware the only installation in Great Britain using group-switches is that of the Glasgow Corporation Tramways Department, the sole reason at the time being to safeguard against the failure of individual switches. With absolutely reliable switches there would be no possible advantage in such an arrangement. Granted that each switch safely and reliably controls its own circuit a duplication of switches is unnecessary and undesirable.

[For further discussion on this paper see pages 238, 247, and 249.]

A paper presented at the 185th Meeting of the American Institute of Electrical Engineers, New York, March 25, 1904.
Copyright 1904, by A. I. E. E.

OIL-SWITCHES FOR HIGH PRESSURES.

BY E. M. HEWLETT.

This paper naturally compares the oil-break switch with the air-break switch. In treating this subject the following points appear to be the main points for consideration:

1—Abnormal Rise in Pressure: owing to the fact that in oil-switches the circuit is opened at the zero point of the wave, the rise of pressure found in the air-break switch is not experienced. This point is of particular importance in high-pressure, long-distance lines, and in cables carrying considerable energy.

2—Capacity: experience has proved that oil-switches may be designed to break circuits of practically unlimited capacity.

3—Length of Arc: owing to the smothering action of the oil on the arc the length of arc under oil is only a fraction of its length in air.

4—Insulation: the insulating qualities of the oil decrease the distance required to prevent leakage and arcing.

5—Size of Switch: owing to the fact that the arc length is materially decreased and the value of the oil as an insulation reduces the creeping surface, an oil-switch can be made very much more compact than an air-switch.

6—Remote Control: the design of the oil-switch lends itself readily to operation by control from a distance.

7—Arc Confined: the fact that the arc is ruptured under the oil within the switch has two advantages; 1st. switches can be placed close together without danger of short circuit; 2d. in case of emergency, confusion is avoided as there is no visible arc to disconcert the attendant.

8—Station Arrangement: the flexibility of the oil-switch places no limitations on the station arrangement, permitting the circuits and bus-bars to be arranged in the most advantageous manner.

9—Isolation of Phases: the possibility of complete isolation of the phases in a reasonable space is easily secured by the use of oil-switches

DISCUSSION ON "OIL-SWITCHES FOR HIGH PRESSURES."

C. C. CHESNEY:—(A) It is quite apparent that in the rapid evolution and in the perfecting of electrical machinery for power-stations, switch and switch-control design have been more or less neglected. On account of the great importance to all power stations of good switching mechanism, the reason for this neglect is rather difficult at this date to understand, although it is evidently more or less due to the apparent simplicity of a rather difficult problem. While dynamo, engine, and wheel design have been reduced to an almost exact science by the best talent of the engineering profession, the switch and the controlling mechanism have been refused the attention they deserve, although it may be safely stated that in power-stations of this country there are more shut-downs due to defective and inadequate switching mechanism than to any other one cause. Mr. E. W. Rice, several years ago in his paper on "High-Potential Control" pointed out the inadequate means at hand at that time for controlling and switching currents of large volume and pressure. In the same paper he described certain switches designed by the General Electric Co., which from extensive tests were believed would meet any and all requirements of heavy station-service. Since then these switches in actual service have fulfilled the designers' expectations. During the same period, the other manufacturing companies specially interested in high-pressure alternating-current machinery have developed high-pressure switches, on more or less different lines, which are believed to be equally good. However this may be, it can hardly be expected that the design of any of these switches is final and that there is no room for further improvement. The following notes are therefore offered in order to outline the more important features and essential elements which have made some of the later switches successful, but without any attempt to describe any particular make of switch or describe any particular switch design.

(B) Types: on American high-pressure transmission lines there are four general types of switches now in use:

1 Switches designed to break the circuit in the open air.

2 Switches designed to break the circuit in an enclosed air-space.

3 Switches designed to break the circuit with the aid of an enclosed metal fuse.

4 Switches designed to break the circuit under oil.

Type No. 1. The large amount of space required by this switch in order to be certain that the arc will be broken makes its use impossible except in rare instances and then it can be used with safety only when the line pressure is comparatively low, for the reason that a circuit containing inductance and capacity may have very high-pressure oscillations set up in it by an open air arc, unless the current is broken at zero value. The result of the increased pressure is likely to be the destruc-

tion of the insulation on some part of the system, probably that of the transformers.

Type No. 2. This switch is a decided improvement over Type No. 1, as far as the amount of space occupied is concerned, but its effect on circuits containing inductance and capacity is very little different from Type 1, so that there will be the same oscillatory rises of pressure and the same destruction of the insulation on opening the circuit. In addition, the explosion on opening heavy currents with this switch is at times so terrific as to endanger not only the switch itself, but all delicate instruments in the immediate neighborhood.

Type No. 3. Two forms of this switch has been more or less used. In the first form the fuse is connected in parallel, and in the second in series with the current carrying parts of the switch. The first form is limited to low-pressure circuits, because of the total unreliability of the enclosed fuse on comparatively high pressures when the circuit is fed from large central stations. The second form operates through the severing of a metal fuse within an enclosing tube filled with powdered carbonate of lime, or some other non-conducting powder. The end of the fuse is drawn through the tube by the moving arm of the switch and the circuit is opened without serious commotion if the switch has been well designed and care has been taken properly to fill the tube. The switch will open safely almost any circuit at almost any pressure, but like the open air-switch is limited by the amount of space required, while the powder set flying by the explosion of the arc is a decided objection if there is any moving machinery in the same room.

Type No. 4. This type of switch has within the past year been almost universally recognized as the only switch to be used for high-pressure work, for the reason that it can be made in compact form at reasonable cost and when properly built will disconnect from the generating system with certainty and safety any circuit under any condition of load, even a low resistance short circuit. Contrary to general expectations, it has been shown by a number of experiments that the opening of a circuit by an oil-switch is not a *quick break*; the oscillograph shows that the effect of the oil is to allow the arc to continue for several periods and then, as a rule, to break the current at the zero point of the wave. As a consequence, the opening of any circuit with oil-switches is rarely accompanied by destructive rises of pressure. The true reason for this fortunate action of the oil-switch is rather difficult to see. One prominent experimenter has attributed it to the " practical incompressibility of the oil, and, in consequence, the gas bubble which is formed at the terminals of the switch is under an enormous pressure and holds the arc up to the next zero value of the current. At the next zero value of current the liquid pressure blows out the arc." Another holds that by the breaking up of particles of oil by the arc, a high resistance conducting strata is formed

between the terminals of the switch, which allows the circuit gradually to discharge itself. It is probable that both of these phenomena may simultaneously enter into the action, because it is true that an oil-switch creates less fuss in the oil if it is opened slowly; but it is also true that an oil-switch for 40 000 or 50 000 volts must have a depth of oil over the terminals of at least four or five inches. If less depth of oil is used, the oil is likely to be thrown out of the oil pots, on the opening of the circuit, although the arc will be broken.

Of the two types of oil switches, used on 20 000,- 30 000-and 40 000-volt circuits, one, the plunger type, breaks the arc in a vertical plane, while the other breaks the arc in a horizontal plane. The plunger type has been used quite extensively in the larger power-stations of the East. The other form has been used more particularly by one or two of the larger Pacific Coast long-distance power-transmission companies. Some time ago the writer had an opportunity to test thoroughly a switch of the latter type on the circuits of the Bay Counties Power Company.

The switch was of the three-pole type and was arranged to break simultaneously the three legs of the three-phase circuit. During the regular running of the plant it had given satisfactory results under rather trying conditions. In order more thoroughly to test the arc-breaking qualities of the switch, one pole was connected across the main transmission line and the line was short-circuited at the full line pressure. The short circuit was then opened by one pole of this switch. As the switch was hand operated, there was no record of the exact time length of the short circuit, but it was not over one second. These experiments were repeated a number of times at both ends of the 150-mile line of the Bay Counties Power Company. Each time the circuit was opened without disturbance of any kind, and, as far as it could be determined, the short circuit was opened equally as well at either end of the line. During these experiments the Bay Counties Company were supplying their regular customers, and were operating at a line pressure between 45 000 and 46 000 volts. All of the alternating current generators at both power-houses were in operation and the output amounted to about 11 000 kw.

Fig. 1 shows one pole of this switch and gives the approximate dimensions. The mechanical construction of the switch is extremely simple. The contact-arm is mounted on an insulator at the end of the vertical operating rod. The outer ends of the contact arm carry fingers, which make contact with terminal-blocks on the ends of the studs which pass through the porcelain insulators to the line. It will be noted that each pole has two breaks in series, each about nine inches long. The switch was operated by rotating the operating rod which moved the contact arm through an angle about 90°. The oil-tank was 28 inches in diameter and there were about five inches of oil over the

contacts. During the test the cover of the switch was off so that the breaking of the arc could be observed. At each break there was a small arc formed at the terminal-blocks, but there was only a very slight elevation of the surface of oil immediately over the arc.

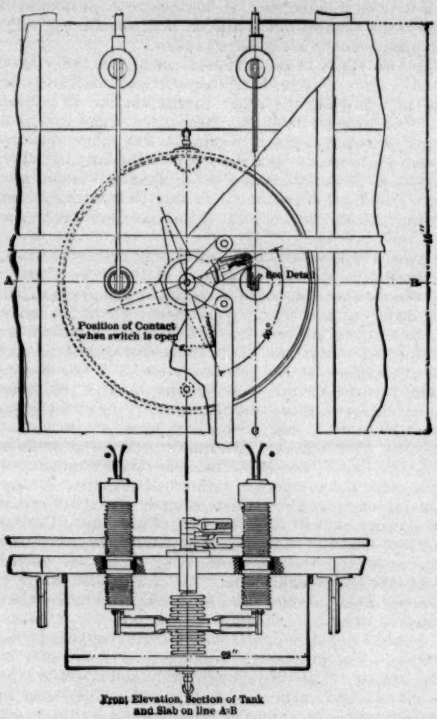


FIG. 1.

(C) On the assumption that the oil-switch, in the present state of the art, is the only switch to be used for high-pressure work, the following points of construction will bear consideration after the particular form of oil-switch has been selected:

1 Rating: The performance of the switch under abnormal conditions of a low resistance short circuit should be considered as well as the capacity of the switch under normal operating conditions.

2 Oil: Any good paraffine oil will answer, but it should have about the following characteristics:

Flashing point	215° cent.
Fire Test	250° cent.
Specific gravity	0.865
Viscosity	———
Acid	None.
Alkali	None.
Evaporation	Negligible.

3 Insulation: The insulators and insulating bushings should be either glass or porcelain. The switch should stand a breakdown test between the live parts and the metal case and framework of at least twice the working pressure. The external terminals should be far enough apart, or sufficiently well insulated, so that there can be no possibility of the current striking across through the air from terminal to terminal.

4 Location: Oil-switches should be placed away from the switchboard as well as the generating and transforming apparatus. Each pole should be placed in a separate fire-proof cell, so that by no possibility can an arc or explosion in one cell be communicated to another or to the neighboring machinery.

5 Method of Operation: All switches should be either magnetically or electrically controlled from a central switchboard, and all the poles of a switch should be operated simultaneously. It is also desirable to equip each switch, especially if it is automatic, with a time-element attachment, so that the circuit cannot be opened for at least a second after the operating mechanism is set in motion.

F. A. C. PERRINE:—The speaker wishes to describe some experiments tried last fall with three oil-switches operating on the same principles as the one Mr. Chesney describes. The three switches were connected up at Mission San José in California, 98 miles from the power-plant of the Standard Electric Company, and the experiments were carried on during the night so that command of the entire generating station could be had. This station contained four 2000-kw. machines. A single handle controlled all three switches so that they opened simultaneously. The three-phase line was first connected through the switches, and the three phases short-circuited at the other side of the switches, thus putting a switch in series with each break. The line pressure was 40 000 volts. The switches were opened and closed about six or eight times that night. Then the work was shut down until the next night, when the switches operating as a short circuit between the wires of each phase could be connected, so that each switch formed a short circuit on a phase, the three

switches short circuiting the entire line, which is very much more severe service than in the former connection. The line was short-circuited and the switches were opened several times, first opening the switches quickly after they had been closed, and afterward holding them in short circuit. The switch operated successfully, the machines held the speed and the voltmeter showed the pressure was held up. The ammeters went off the scale at 12 500 kw. Finally the experiments were discontinued because at the power-house end of the line the lightning-arresters arced over. These were a series of the so-called Dutch-horn lightning-arresters which, especially for the experiments, were set 4.5 in., so that from line to line the gap was nine inches. The arc in almost every instance when we opened the switch went across these lightning-arresters and finally they were destroyed, the pole head was destroyed, and the No. 0 ground wire was entirely fused. The superintendent said that the appearance at the station was as though the sun had come down in the back yard. The interesting thing was that those switches did not fail to open the circuit on any one of the experiments, and the experiments were only discontinued on account of the danger to the generating and transformer apparatus due to the apparently high-pressure as shown by the current jumping across nine inches of open air space.

ALEX DOW:—In his opinion the oil-switch had definitely arrived—it was not merely coming. In Pacific Coast installations visited within the past thirty days he had found the air-break switches carefully tied up so they could not be operated; and in series with them, oil-break switches which were regularly used. This substitution of a nine-inch oil-break for a six-foot air-break was general on the Pacific Coast.

RALPH D. MERSHON:—Referring to Mr. Hewlett's paper, the speaker did not agree with Mr. Dow that the oil-switch has necessarily come. It has come for some pressures, but not necessarily as yet for 30 000, 40 000, or 50 000 volts, as any construction which in the present state of the art means going into cables with high pressures is objectionable. With such oil-switches as the speaker is familiar with, this is necessary or else a large amount of space for their wiring and installation becomes necessary. If an oil-switch could be put up in the roof truss of the building, being made as it were a part of the high-pressure conductors,—then it seems that the oil-switch would be a very advantageous piece of mechanism to use in connection with high-pressure plants, but until that is done it does not appear attractive.

C. F. SCOTT:—So much has been said about the oil-switch and so little that was favorable about the air-switch that the speaker thought of asking Mr. Nunn to say a few words on the subject. The air-switch a few years ago was introduced in high-pressure work when there was no oil-switch for that work, and it seems it still has a large field of its own in places where the

pressures are high and the amount of power as for instance in small sub-stations, is small; where the oil-switch, as developed now, will be too expensive to install. In the first high-pressure plant of 40 000 volts, installed at Provo, Mr. Nunn had certain air-switches which it is understood rendered excellent service.

P. N. NUNN:—The impression is conveyed by Mr. Scott that a defence of the air-switch may be expected. The high-pressure air-switches at Provo are rapidly being replaced by oil-switches. This is in order to avoid the line disturbances caused by air-switches, and also in order to substitute the automatic feature of the oil-switch for the fuses necessary with air-switches. It is true that oil-switches are very expensive, but, while a reduction in cost will be most welcome, even at present prices, they will undoubtedly be used in all future high-pressure work.

C. L. DE MURALT:—The speaker's firm uses both oil-type and air-type switches, the former in preference in all important installations, at least in the main leads. But there are cases where it would be very expensive to have oil-switches in every single place where the current may have to be interrupted at some time or other. Therefore, in places where such interruptions occur only once in a great while, or only in cases of an emergency, he sometimes, when economy is necessary, employs switches which resemble somewhat the horn-type of lightning-arrester. The main part is in fact built exactly like one of these lightning-arresters, the air-gap being bridged by a terminal part which, when the switch is actuated, is drawn away. The arc then breaks itself by drawing toward the upper ends of the horns, which are wider apart. The current of a 1500-kw. generator at 26 000 volts has been ruptured in this way, which is a fairly severe test. For oil-type switches he uses a switch which can either be manipulated manually or mechanically or automatically as a time-limit overload switch. The latter arrangement is as follows: the switch is held in position by a tripping device. If the latter is tripped a spring will open the switch. That tripping can be done either manually or by means of a magnet. The magnet in its turn can be energized either by directly closing a switch in the circuit providing it with current, or by a relay, the latter being actuated by overload currents. These currents set up in the relay a magnetic field which tends to turn an aluminum disc and the turning of this disc winds up a weight. As soon as the weight comes to its top position it closes the relay circuit. If the overload is very heavy the disc will revolve very fast, and thus the switch will be quickly released. If the overload is light, it may happen that it ceases before the weight reaches the top position and it will then re-descend and the switch will not be tripped. This constitutes an absolute time element overload relay, and makes out of the switch an ideal automatic circuit-breaker.

[COMMUNICATED BY LETTER.]

H. F. PARSHALL:—Before the perfection of the oil-switch, the air-switch with long break and large clearance for flaming was the most reliable device and many of the early installations owe their success to the use of the air-switch. Subsequent experience gained is that oil-break switches can be installed in a great deal less space and can be depended upon to open the circuit with much less damage to the switches. The one condition which his experience would lead him to impose in connection with oil-switches is that there must be absolutely no inflammable material in the switch other than the oil; that is to say, the use of wood and such like materials for separators and insulators is to be avoided.

In a brief written communication A. R. Henry described a switchboard of the Canadian Electric Light Company's powerhouse, Chaudiere Falls, Quebec.

[For further discussion on this paper see pages 242 and 249.]

A paper presented at the 185th Meeting of the American Institute of Electrical Engineers, New York, March 25th, 1904.
Copyright, 1904, by A. I. E. E.

TERMINALS AND BUSHINGS FOR HIGH-PRESSURE TRANSFORMERS.

BY WALTER S. MOODY.

This subject will include cables, straps, connectors, etc., for both high- and low-pressure side, designed both for terminal connections and for changes in the ratio of transformation, together with their insulation. In transformers for moderate pressure and having but two high- and low-pressure terminals, the problem of terminals is a simple one; with higher pressures and numerous changes in the ratio, however, the design of these parts of the transformer often becomes a most difficult problem, upon the proper solution of which depends, to no small extent, the reliability of the transformer.

Location of Terminals on Coils.

It is much better to have the high- and low-pressure terminals at opposite ends of the structure, for it is almost impossible to keep safe distances between the terminal and connecting coil leads when all are at one end. In a shell-type structure, having its coils in a vertical position, this requires one set of coil terminals to be at the bottom of the case, but to bring these safely to the top is not as difficult as to separate high- and low-pressure conductors that are at the same end of the windings.

Insulation of Terminals on Coils.

In an oil-immersed transformer, this presents little difficulty, as it is simply necessary to have all leads rigidly spaced a safe distance from each other and from the coils, and covered with sufficient waterproof insulation to prevent any moisture penetrating the coil around the terminals before the oil is put in.

In air-blast transformers, however, the case is different; here all terminals must be covered with an insulation integral with that on the coil itself, to a distance from the coil that provides sufficient surface insulation, even when the lead is well covered with dust and dirt.

Often the dielectric strength of a transformer is materially lowered by allowing the coil-terminals or taps to project beyond the sides of the coils, thus shortening the distance between primary and secondary. "Spreading" the exposed ends of the windings removes this difficulty, except when the terminal comes from a point well within the coil, but introduces a more serious defect, lack of rigidity to withstand the strains of short circuits. Usually the problem can be solved by so winding coils as to have only outside terminals and locating such coils as have taps on the outside of the coil structure.

Location of Main Terminals.

The best location for these naturally varies with the type of transformer and its pressure; for the air-blast type, the air-chamber forms a convenient and natural location for the low-pressure wiring, and the terminals of these are therefore usually located in the base of such transformers and made accessible by doors in the side of the base. For pressures not exceeding 25 000 volts, the high-pressure wiring can also be placed in the air-chamber, without making the air-chamber of excessive cross-section, so that all transformer terminals are in the base and exposed wiring is avoided. Heavy rubber-insulated cable is to be avoided in such construction, however, for should the rubber take fire from short circuit or other causes a draft of air will carry the fire rapidly along the duct and into the transformers.

In oil-filled transformers the terminals are, of necessity, located at or near the top of the case. Often for convenience in external wiring, projecting pockets are provided through which terminal-leads may leave the case in a downward direction. With such construction, it is necessary to have a solid section in the cable, just above the oil line, and to have this section insulated or covered with an insulation impervious to oil, otherwise the cable and insulation will act as a siphon and discharge oil.

Insulation of Main High-Pressure Terminals.

Below 40 000 volts, the insulation of terminals offers no special difficulty; porcelain or glass bushings can readily be obtained that are safe for this pressure, even if the conductor

has no insulating covering. For higher pressures, the problem is more difficult. If no insulation is used on conductor, the bushings become expensive and so large that there is scarcely room on top of a moderate size transformer for as many terminals as are often required. The following are some of the more common forms of bushings that have been used:

Wooden tubes;

Hard-rubber tubes;

Glass and porcelain tubes, both single and concentric;

Numerous forms of molded porcelain bushings.

Wooden tubes of the necessary size cannot be thoroughly dried and filled. Hard rubber is also apt to contain impurities that it is unsatisfactory; moreover, it deteriorates rapidly if ozone is generated near it. Glass is fragile and must be protected with other semi-insulators. Porcelain, or any smooth tube, must be very long if it have sufficient leakage surface to be safe when dirty, and even the best shapes of corrugated bushings are large and expensive when capable of withstanding a test of from 75 000 to 160 000 volts. All things considered, the writer has found the following practice quite satisfactory for test-pressures not exceeding 160 000 volts.

Insulate the lead with varnished wrappings that will safely withstand for one minute about half of the test-pressure to be applied, bringing out this lead through a porcelain bushing having the same strength as the insulation of the lead, and sufficient surface to prevent leakage at this pressure when dirty; in other words, let the insulation of the leads be sufficient for the working pressure, and the porcelain be of such strength as to give the factor of safety desired. This combination forms a far safer insulation than a bare conductor and a larger bushing which would stand the same puncture test as the combination, from the well-known fact that oxidized linseed oil is an insulation that will momentarily stand several times as much as it will for any considerable length of time, while porcelain, glass, etc., have no such time-factor.

In leads requiring a test of 100 000 volts or more, and insulated in this manner, an additional difficulty is met in the induced charge on the outer surface of the insulation; at this pressure the surface is covered with a heavy brush discharge that so reduces the surface resistance to leakage that 100 000 volts will travel along several feet. It is usually impracticable to make the insulated lead long enough to withstand the pressure under

these conditions, but the discharge may be broken up, so that it will not appreciably reduce the surface resistance, by bell-shaped pieces of rubber, porcelain, or other insulation slipped over the lead before all the varnished wrappings are put on, and having its small end so shaped as to allow of its being buried in the outer wrappings.

In transformers designed for Y-connection and grounded neutral, some transformer builders, in order to save expense on high-pressure bushings, have grounded one terminal on the case and insulated only such leads as are to be connected to the line; this prevents operation with Δ-connections, but otherwise seems unobjectionable. In similar manner, the use of three-phase transformers with the inter-connecting between the phases made within the case reduces the expense and possibility of trouble with bushings.

Eighty thousand volts is the highest pressure that is now practicable for transmission work, but transformers and insulators must be tested, consequently there is some demand for transformers working up to 200 000 volts. The insulation of the terminals of such transformers is the most formidable part of their design. As yet, I know of no satisfactory solution of the problem except to use oil-filled tubes as terminals. A terminal that has withstood 375 000 volts without any indication of weakness is constructed as follows:

The tube was the shape of two truncated cones, bases together; about 12 inches in diameter at the centre, and four inches at either end; it was built up of thin wooden rings, telescoped a short distance into each other, and held together by the conductor which, for mechanical purposes, was made quite heavy, and which was located in the axis of the cones and supported by washers at either end of the tube; between each section of the tube were collars of insulating material, some three inches larger in diameter than the tube, which served the purpose of greatly increasing the leakage surface. After the sections were drawn tightly together by nuts at each end of the conductor, the whole structure was repeatedly dipped in varnish and dried, thus sealing all joints. The terminal was mounted with the lower end several inches under the oil in the transformer and with its largest diameter on a level with the cover; the lower end of the tube was tightly sealed, making the tube perfectly oil-tight.

Internal Terminals.

At present we are passing through a period of development in

line construction. Each engineer of a new transmission system of considerable length desires to use as high pressure as possible with a line construction of reasonable cost, but few are sure whether 50, 60, 70, or 80 thousand volts is the safe maximum for their conditions. It is common, therefore, for the manufacturers to be asked to make transformers that can be operated at several voltages on the high-pressure side. The result, whether accomplished with series-multiple connection, changing from Δ to Y, or simply by taps, usually requires so many terminals, that it becomes quite impracticable to place all the necessary leads outside of the case, even were it desirable to do so; consequently, accessible terminals inside the case must be provided. Again, at these and lower pressures also, it is usually desirable to provide for limited range of adjustment in the ratio, say by 2% steps, with a total of 10%; such changes are usually too small to be made except by means of taps on the high-pressure windings. Except in transformers of very large capacity, there would be no room safely to insulate so numerous terminals above the surface of the oil; the practice is therefore to locate such terminals just under the oil and make them as accessible as possible, either by the removal of the transformer top, or through an auxiliary cover on the top of the case. It is better that each of these terminals be separately supported by glass or porcelain insulators; for a single support, such as a slab of marble, is almost sure to collect sufficient semi-conducting material to cause trouble sooner or later. Such terminals being, at best, rather inaccessible there is danger that a wrong or imperfect connection will be made when changes are desired. The following method of mounting transformers in the tank greatly simplifies the problem of getting at such terminals, especially when transformers are installed under a crane: instead of supporting the transformer proper on the base of the case as usual, it is hung from a strong cover; the interior terminals are placed in about the usual position, but are supported by the bolts carrying the transformer. To get at these terminals it is then simply necessary to raise the cover with the transformer, until the terminals are on a level with top of case; connections may then be made with convenience and safety and the transformer returned to its position in the tank.

Low-Pressure Terminals.

Usually these present no special difficulties; when transformers are connected in multiple and deliver 500 amperes or

more, special caution should be taken that all joints are soldered or that terminals are of such construction as to have extremely low contact resistances. Taper plugs and receptacles are perhaps the most reliable form of contact for the purpose.

Current in excess of 500 amperes should never be brought out through separate openings in the case, otherwise there will be local heating around the terminal and needless reactance introduced into the circuit. Currents over 2500 amperes should be brought out by means of intermixed bus-bars for the same reason.

DISCUSSION ON "TERMINALS AND BUSHINGS FOR TRANSFORMERS."

RALPH D. MERSHON:—In Mr. Moody's paper there is one point in regard to the terminals for high-pressure transformers with which the speaker thoroughly agrees. The speaker considers that the marble terminal board has no place in high-pressure transformers. The leads should be brought out to porcelain insulators located underneath the oil, each to its separate insulator. In a number of cases troubles have occurred on marble terminal boards, at times too difficult to remedy. A marble terminal board scored by a discharge and afterward apparently made perfectly clean by scrubbing, will not stand the normal pressure when again put into service, and the only way in which it can be made to stand is to chip out the marble where the discharge occurred. Instead of using rubber-covered cables in air-blast transformers for high-pressure terminals, as Mr. Moody suggests, the speaker prefers to have these terminals come out into the air and remain bare during the rest of their course to the sub-station or the next bank of transformers.

C. E. SKINNER:—Every transformer designer who has had to do with pressures of 20 000 volts or over appreciates the difficulty of bringing out the high-pressure terminals from such transformers. It not infrequently happens in extra high-pressure work that the size of the transformer, and particularly the containing case, is materially modified by the requirements for bringing out the terminals. In the case of air-blast transformers pressures are limited by the tap to an amount which makes the problem comparatively simple, provided a large number of ratios have not been required to increase the flexibility of the system.

In the case of oil-insulated transformers the pressures have already gone as high as 55 000 volts in actual service, and higher pressures are now being seriously considered. As stated by Mr. Moody in his introduction to the discussion on this subject, these higher pressures present a very formidable problem to the designer, and this difficulty is sometimes still farther increased by the requirements for the transformer case to be able to withstand considerable mechanical pressure. Mr. Moody has mentioned some common forms of bushings, which have been used for the purpose of insulating the main high-pressure terminals. Wooden tubes alone are not satisfactory for pressures, which at the present time may be considered as high. Hard-rubber tubes deteriorate rapidly. Glass and porcelain are mechanically fragile, and it seems next to impossible to get a moulded porcelain of sufficient dimensions for some of the higher pressure now being required.

As a general proposition it is necessary for the higher pressures that the distance between the high-pressure conductor and the metal of the case, where the conductor passes through, must be of such a value and the material of such quality that there will be no appreciation brush discharge at this point. Where

the transformer tanks are not required to withstand heavy pressures a satisfactory construction consists in fastening a slab of insulating material, such as marble, in the top of the cast-iron cover into which are placed heavy tubes for the conductors with sufficient extension to give the necessary surface insulation. Tubes made up from alternate layers of varnished paper and mica have proved very effective. In one instance where the line voltage was 50 000 the transformer case was required to withstand a pressure of approximately 100 pounds per square inch. In this instance the marble slab mentioned above was not allowable on account of the mechanical pressure requirements and the problem was solved by making extra heavy bushings, which passed through stuffing-boxes arranged to clamp the tube very tightly. This has given excellent service.

An interesting example of bushing trouble occurred on a 55 000-volt line where the bushing consisted of a glass tube with 0.625-in. wall incased in a heavy wooden bushing for mechanical protection, the combination being set in a wooden cover. The static discharge over the surface of the glass tube scored the tube to a depth of 0.0312 in. to 0.0625 in., making the surface rough and finally a breakdown occurred directly through the tube, shattering it into many pieces. This shows that glass has a time-factor at extra-high pressures.

Mr. Moody mentions the complication frequently imposed in the construction of the transformer itself by requiring combinations for various pressures and for a slight amount of regulation by bringing out taps from the high-pressure windings. From the designer's standpoint the speaker wishes to protest against this practice of requiring almost universal flexibility. After the transformers are in service the operating man considers that the paramount idea is continuity of service. Every extra lead and tap complicates the design and makes the construction more expensive and difficult. It is possible, of course, to secure great flexibility by such means, but the chances of trouble from those leads and taps which are not in service, and the possibility of making a wrong connection, greatly increase, and it is the speaker's experience that in many cases where such elaborate systems are required they are never used.

[COMMUNICATED BY LETTER.]

IRVING A. TAYLOR:—Instances have been noticed in air transformers where an uninsulated or lightly insulated tap is brought out through the external coil insulation and a lead soldered on and the joint insulated. This leaves a weak spot on the lead insulation just where it enters the coil insulation. Leads should be heavily insulated to a point well within the coil-jacket and should pass through the latter in a slanting rather than a straight direction, so as not to leave a vulnerable point in it at the point of entrance,

In some cases internal leads are brought up through the top

layers. This is a grave source of weakness as it gives a creeping surface through the inter-layer insulation. It also makes it necessary to wind the upper layers around it, and these are therefore liable to be crushed together. Taps from inner layers should always be brought out from the end of the layer, and in such a manner as not to cut the inter-layer insulation.

Where main terminals are located in the path of the air-blast, a great deal of surface dirt and consequently a long, creeping surface should be reckoned on. Terminal boards in air-blast transformers for this reason appear to be a source of danger, and where there are not many terminals it would seem best to use cables with heavy caps, the joints being made inside the case and above the fire-damper, if such is used. Fire-proof cables should be used in or near the air chamber.

Leads from oil transformers give a great deal of trouble by syphoning oil, and it is not at all easy to suggest a certain way of stopping it. Mr. Moody's remark that a solid section in the lead is necessary is correct; but it is difficult to insulate this section in practice so that the oil will not creep between the layers of insulation and on to the stranded cable. After a good deal of experimenting, the writer used a porcelain tube (filled with sulphur) over this solid section, and found it to be about the only successful method of stopping creepage. Bushings through the case should be extended well above the iron and the cable should be sealed in with non-solvent, insulating compound (sulphur may be used), so arranged as not to pocket any oil, but to drain it off. It is best not to have the braided covering of the lead extend inside the case as it is liable to carry oil out.

Where transformers are connected to outdoor leads they should have a solid section, well covered with water-proof material, in the external lead, as water will follow through a stranded cable for a long distance and in large quantities. This is a frequent source of burn-out in cable heads, etc.

All transformer cases should be grounded to prevent fire and make them safe to handle. Attention should be given to the fact that the ground wire should be heavy in proportion to the circuit protecting devices used. Thus, a No. 8 wire should not be used on transformers protected by 300-ampere fuses on the secondary side. The ground connection should be electrically sufficient and its resistance should be tested to determine this, a moderate pressure being used.

Where rubber-covered leads are used, the rubber should be heavy (not less than 0.25-in. wall per 10 000 volts) and of high quality, and fire-proof covering should also be employed. Extra flexible cable is usually preferable.

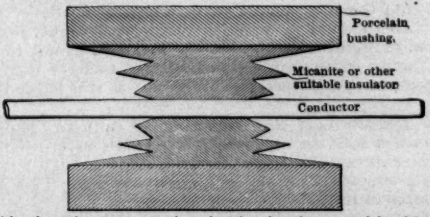
While taps allow one of the greatest advantages of the transformer to be utilized—that of obtaining different pressures from the same apparatus—it seems as though many specifications require more taps than are actually necessary. Taps cost money

on account of the necessary space, and besides are nearly always a source of weakness. They should therefore be avoided unless their use is absolutely justified. Except where transformers are to be used partly as pressure regulators, one 5% or 10% tap should give sufficient adjustment of ratio to meet lighting or railway conditions. Mr. Moody's remarks regarding the use of separate porcelain insulators instead of terminal boards are entirely correct. The writer thinks that the necessity of using a crane and taking a transformer apart to change or make internal connections, is hardly justified. Transformers should always be tested before connecting to their bank to discover wrong connections.

[COMMUNICATED BY LETTER.]

N. M. SNYDER:—The writer suggests that the design of the high-pressure insulator be drawn on—for meeting the conditions—without resorting to the oil-filled tubes for high-pressure terminals. First by making a suitable insulator for the glazed porcelain bushing, *e.g.*, to fit inside, having the conductor passing through its centre.

The insulator being double petticoated as the cut shows, gives a much greater resistance path than the straight bushing.



Side elevation cross-section showing insulator and bushing.

In bringing out heavy currents from transformers in multiple he concurs with the idea of sub-division of terminals, while it may introduce the necessity of more openings it has the advantage of distributing the load more evenly on the windings, assures less local heating and greater terminal surface for cooling.

[COMMUNICATED BY LETTER.]

A. C. PRATT:—In considering the location of internal terminals in transformers one point might well be brought to the attention of the designer of relatively high-pressure apparatus.

Many transformers for power transmission are provided for adjustment of pressure with taps on the high-pressure winding for cutting out perhaps 10% to 15% of the winding. These

adjustment taps are usually either in whole or in part located on the outer coils nearest the line terminals. If the line terminals be connected to a pair of these taps, cutting out say 5% on either end of the coils, then the maximum pressure to ground within the transformer becomes 10% more than from either line wire to ground. This material increase of insulation strains is especially undesirable in high-pressure transformers, where small brush discharges become troublesome, not only in air-cooled but also in oil-cooled transformers. Moreover the outer turns near these taps must be heavily insulated from one another to withstand lightning and other static strains.

If all these taps be made on adjacent ends of coils nearest the middle of the total winding, then the internal pressure in the transformer never exceeds line pressure; lightning strains are confined to the outer ends of the end coils, and when the taps are connected to cut out, say 10% of the total turns, the effect is merely an electrical over-lapping of the turns which are cut out, and the latter, if of equal number on the two adjacent coils, might even be connected in parallel, saving, in this assumed case, 7.5% of the $I^2 R$ loss in the high-pressure winding.

As to bushings, glass is being rightfully tabooed; it is fragile and necessarily of too small a diameter, thus naturally carrying too dense a charge on its surface, as noted in the paper. The tube is a condenser, the entire bore being at the pressure of the wire, and some other pressure, usually ground, applied near the middle of the outside of the tube. Charging current flows to and from the ground, along the tube, held close to the smooth surface of the glass, thus breaking down a thin film of air. The thinness of the film may be illustrated by wrapping strips of tape around the tube, when, upon applying test-pressure, the breakdown discharge will pass between the glass and the tape.

The remedy is, first, to increase the thickness of the tube wall thus decreasing the capacity (which is also affected by the kind of dielectric employed) and at the same time increasing the surface along which the charging current will flow, thus in two ways decreasing the current density on the surface of the bushing; secondly, further to break up and dissipate the surface-charging current by insulating rings set approximately at right angles to the axis of the bushing, as suggested in the paper.

It is essential that the wall of the tube be so made as to avoid long, thin air spaces extending along the axis of the tube, as these will be the seat of local currents, which may lead to the failure of the whole bushing.

[For further discussion on this paper see page 243.]

MEETING AT CHICAGO, MARCH 29, 1904.

Discussion on "The Relative Fire-Risk of Oil- and Air-Blast Transformers."

James Lyman:—The following features should determine the selection of transformers, as well as other electric apparatus:

1. Reliability of service, including capacity for all probable overload conditions of practice.

2. Efficiency, regulation, the low rise in temperature under the various operating conditions.

3. Safety against personal danger to operators and safety against fire-risk, either from internal or external cause.

4. Compactness, simplicity of design, easy access to parts, and general cleanliness.

In small sizes the external surface of well-designed transformers is ample to radiate the heat due to copper and iron losses. The radiating surface per kilowatt, however, rapidly diminishes as the capacity increases, and in large sizes, from 1000 kw. up, it becomes absolutely necessary to carry off the heat by some circulating fluid, such as air, blown directly through the coils and the iron core, or water circulating in a coil of pipes suspended in the oil. While in transformers from 50 to 300-kw. capacity, it is perfectly practicable to design them of the self-cooling oil type, it is frequently more desirable to have them cooled from some entirely external source, such as by air-blast or water, as they can then be installed in a limited space where proper surface radiation cannot normally be obtained. The air-blast transformer has the advantage over the oil- or water-cooled type in being pretty nearly fire-proof. The insulation on the winding is the only combustible material in its construction, and this amount is comparatively small. Burn-outs in properly designed air-blast transformers are exceedingly rare, due to the fact that a comparatively low temperature can be maintained even under heavy overloads by varying the air-blast. The power required for driving the blowers is generally from 0.1 to 0.3% of the rating of the transformers, according to their sizes, so that the power required need not be considered in the efficiency of the transformers. In cases where burn-outs have occurred in air-blast transformers the writer does not know of an instance where the fire has extended beyond the damaged transformer, the shell of the air-blast transformer acting as a good fire-proof casing, and in case of external fire the air-blast transformer is seldom seriously damaged. When properly designed for thorough circulation of oil through the core and around the coils, and with properly-designed tanks, oil-cooled and water-cooled transformers should not offer serious fire-risks. The speaker believes that within the limiting pressure for which air-blast transformers can be used they are decidedly preferable to the oil

cooled. They are clean, compact, thoroughly reliable, and fully equal in efficiency and other characteristics, and, if anything, capable of greater overload abuse than the oil type. Above 30 000 volts the oil-cooled and water oil-cooled transformers must be used.

W. A. BLANCK:—In regard to the two types of transformers for transmission plants mentioned in Mr. Rice's paper, it is the speaker's opinion that a pressure of 30 000 volts forms the upper limit for the air-blast and the lower limit for the water-cooled oil transformer.

If the transformers be installed in the power-house and not separated from the engine-room by a fire-proof wall, the speaker is in favor of air-blast transformers on account of smaller first cost, convenience in securing proper attendance, and the considerably smaller fire-risk due to the small quantity of inflammable material.

If conditions call for a separate transformer house without special attendance, the speaker is in favor of water-cooled oil-immersed transformers set over suitable trenches so that any overflowing oil would be properly discharged outside of the building. The principal trouble encountered so far in oil transformers seems to arise from external sources, such as arcing switches and lightning-arresters mounted on wooden frames near the transformers. To overcome these fire-risks it will be necessary to use oil switches in brick compartments and to install all wiring on insulators carried by iron supports. Moreover the most essential requirement is to make the transformer house completely fire-proof.

If for any reason self-cooled oil transformers are installed, the cases, if made of corrugated iron, should be strong enough to withstand external heat and should also be set over a suitable trench to discharge any overflowing oil. A fireproof housing is also greatly to be desired.

P. JUNKERSFELD:—One advantage of the oil-cooled type would appear particularly in those instances where large currents are taken from transformers for synchronous converters, at comparatively low pressure. Connections of sufficient current carrying capacity for 1000 kw. at 160 volts, would be difficult to bring into the top of an oil-cooled transformer.

Under such circumstances the air-blast type would have the advantage of making possible a shorter and more satisfactory heavy copper connection between transformer and synchronous converter.

G. N. EASTMAN:—He asks if any one has ever seen an oil-cooled transformer burn up; that is, the oil actually take fire and burn.

D. W. ROPER:—A case of that kind occurred in the East some time ago. A large single-phase, low-pressure transformer had the two sides of the secondary circuit brought out through different holes in the iron case. The hysteresis loss

in the iron produced enough heat to start a flame at one end, but the transformer did not burn up. The circuit was opened and the blaze was smothered.

In another case at the same plant an oil-cooled transformer of an early type was cooled by means of a water coil, in a tank removed from the transformer. An electric arc in the chamber in which the transformer piping was located burnt a hole in the pipe, which led from the transformer to the oil-tank. There was no check-valve in the pipe, and the arc set fire to the oil. The blaze continued until all the oil in the tank was consumed. This took some time, and in the meantime the switchboard operator tried to pull switches in the endeavor to put out the arc. Long before the fire stopped every switch in the plant was open. Those are two cases where fire occurred without destruction to the transformers.

G. H. LUKES:—If a device for smothering a fire in air-blast transformers is desired, use might be made of carbonic acid gas, which is easy to obtain. In case of a fire in an air-blast transformer, the air could be shut off and the carbonic acid gas turned on, when the fire would be quickly put out.

DISCUSSION ON "GROUP-SWITCHES IN LARGE POWER-PLANTS."

W. G. CARLTON:—In laying out a distributing system for high-pressure work, simplicity should be aimed at in the switching arrangements at both the generating and receiving ends of the lines, and also in the way of avoiding taps on the lines as far as possible. If the system is of any size, conveniences for testing should be provided so that no unnecessary time will be lost in starting up the system after a shutdown, and also so that in case of trouble on a line the latter can be easily and quickly tested without interfering with the operation of the rest of the system and without danger to the persons making the test. This matter is frequently lost sight of in the design of a station, and the men who must operate it are placed at a disadvantage.

Oil-switches on high-pressure lines are commonly provided either with a straight overload tripping attachment, with an overload time-limit element or with no overload at all. If it is necessary to use any overload device, and it frequently is, it should have a time element depending on the load. To illustrate: if the normal maximum is 300 amperes, the overload should be set so that it would hold 450 amperes for three seconds, but would open instantly on 700 amperes. These figures are used for illustration and would vary with conditions.

The straight time-limit device is all right in case of an overload, but if this overload approaches short-circuit conditions, the switch will not open before the overload has dropped the pressure on the system sufficiently to cause synchronous apparatus to drop out of step. This has caused the abandonment

of straight time-element overload devices in the care of one station.

Underground high-pressure transmission lines should be carefully protected in manholes, both to provide against fire spreading from one cable to another and also to confine the arc in case a cable burns out. In the case of an unconfined arc if the system is of any size, excessive pressures are likely to be set up due to resonance, and the insulation of other cables and apparatus is likely to be broken down. Various forms of protection have been used. One of the best is split vitrified clay tile, using 45-degree elbows for the bends in the cable. When carefully installed, this gives practically a continuous conduit line through the manhole. On long lines the lead sheaths of transmission lines should be broken at suitable intervals to prevent the flow of stray currents.

P. JUNKERSFELD:—In connection with Mr. Stillwell's paper, he would like to emphasize the fact that it is difficult to discuss this problem without referring to a particular case. Mr.

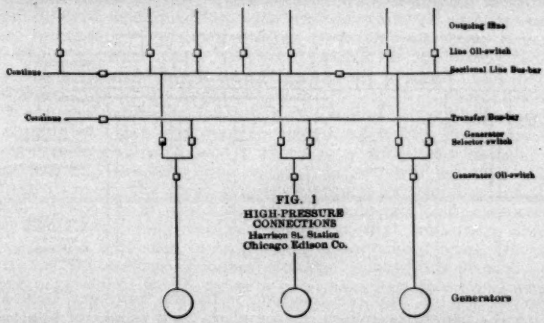


FIG. 1
HIGH-PRESSURE CONNECTIONS
Harrison St. Station
Chicago Edison Co.

Stillwell selected the case of a large power-house for street-railway systems. The conditions were known; that is, the load was pretty well known in advance, and the location of the sub-stations and the arrangement of the system could be figured out quite closely in advance. It was a conversion from steam to electric motors in the case of the Manhattan system and with the road in operation they could determine readily the load on transmission system. Likewise with the Metropolitan.

In a central-station system engaged in the lighting and power business for instance, the conditions are somewhat different. It is not only a problem of designing the switching apparatus for conditions as they then appear, but also of meeting the conditions that arise in a rapidly-growing system.

Due consideration must be given to the percentage of total investment involved in different parts of the system. For instance, an additional investment in switches would often be small compared to an additional investment in lines. Therefore, while the number of long lines and the number of generating units are comparatively few, it will very often pay to introduce more flexibility in oil-switches and bus-bars.

To illustrate, in one of the Chicago stations, which is developed to its ultimate capacity, the high-pressure switching apparatus was entirely rearranged and overhauled during this last year. In that case the problem was not difficult and somewhat similar to that cited by Mr. Stillwell. The solution, however, was slightly different. Instead of the group-switch arrangement, a sectionalized bus-bar scheme was used as shown in Fig. 1. This line bus-bar is sectionalized in such a way that each generator may be made to supply its own section independently if desired. The transfer bus-bar can be divided into two sections only. Each generator has two selector-switches by means of which it can be connected either to its

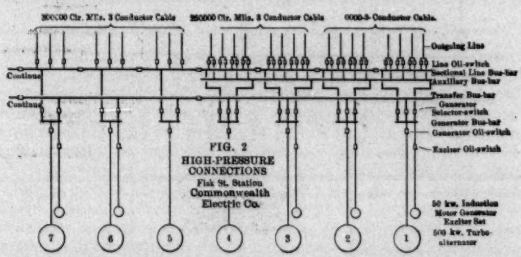


FIG. 2
HIGH-PRESSURE CONNECTIONS
Fisk St. Station
Commonwealth Electric Co.

own section of the line bus-bar or to the auxiliary bus-bar. With the generator-switch open and the two generator selector-switches closed, we also have a tie between a section of the line bus-bar and the auxiliary bus-bar. While each line has only one switch, there would, in case of trouble on line, always be two switches in series as the tie-switch would be used to cut off the section having trouble, in case the line-switch failed. This case is the Harrison Street Station of the Chicago Edison Company. The conditions were fairly well known when the overhauling was done, and the general design was, therefore, a comparatively simple matter.

In another case, the Fisk Street Station of the Commonwealth Electric Company, it was somewhat different. The scheme adopted is a little more complicated, at least it will be during the earlier development of the station. As the station grows larger, any one generator or line going out of service is a smaller percentage of the total and will not cripple

the system so seriously as in the first few years. The scheme is similar to the one previously outlined and shown in Fig. 1, except that there is an additional bus-bar introduced.

As shown in Fig. 2, there is a sectionalized line bus-bar, a transfer bus-bar and a third bus-bar known as an auxiliary bus-bar. In this case, there are three instead of two generator selector switches, and two instead of one line switch. One or more lines can be connected to the transfer bus-bar only through the medium of the generator selector switches, which under that condition perform the function of so-called group-switches. The installation of selector switches on each line and of the auxiliary bus-bar introduces a little more complication than the scheme shown previously, but the total number of switches is not greater than used in most high-pressure stations, having same size of generators and number of lines. Ultimately it is hoped to have simply the sectionalized line bus-bar and the one transfer bus-bar similar to the scheme shown in Fig. 1.

W. A. BLANCK:—Mr. Carlton's remarks in regard to time-limit devices in connection with high-pressure oil switches are very interesting, but disappointing to learn that these devices in which so much hope has been placed for the satisfactory operation of a high-pressure distributing system have been discarded. Why has this been done?

W. G. CARLTON:—In regard to the straight time-limit switch, a number of cases of trouble occurred, such as a short circuit on an underground line. If there is a time-limit switch on that line and the time limit is held on and will not allow the switch to open, the short circuit will work back and affect the whole bus-bar with which the line is connected, and, as a rule, will shut down everything running on that bus-bar. There have been a few cases of trouble on underground lines, not exactly in the nature of short circuits, possibly a ground, or something which would cause a good heavy overload and when the time limit has not been on, the switch has opened and cut out the line; when it has been, it has shut down everything on the bus-bar.

W. A. BLANCK:—Could not that difficulty be overcome by the proper setting of the time-limit devices, for instance the feeder-switches for two seconds and the generator-switches for four or six seconds?

G. N. EASTMAN:—The trouble with setting the time-limit switch for any given predetermined time is increased by the size of the system and the manner in which the lines are run. Conditions will arise in almost any system where there will be time-limit devices on lines which normally are not in series but under conditions of short circuit will be fed in series. The result is that other circuits are interrupted which have time-limit devices on them and always will be interrupted unless on that circuit on which the short circuit occurs, the time limit is set so that it operates before all others. One

can readily conceive how impossible it will be in a large system to vary the time so that these different time-element devices would be caused to operate for the location at which there is a short circuit.

P. JUNKERSFELD:—It seems that the original time-limit device was developed when the high-pressure system on which it was used was comparatively small and had comparatively few lines or branches. As the systems grow much larger, particularly in the cases cited by Mr. Carlton and Mr. Eastman, the straight time-limit relay is satisfactory for overload, but it is unsatisfactory for serious trouble on cables. Before such a time limit operates a good many things happen and it is necessary to have a device which will open very quickly and positively.

W. G. CARLTON:—In the matter of the time limit, if the time is at all appreciable, before that time has elapsed with a heavy short circuit, unless there is a very large amount of power on the bus-bar, the pressure on that bus-bar will drop sufficiently so that synchronous apparatus will all be stopped. That is one of the serious objections to a time-limit device.

DISCUSSION ON "OIL-SWITCHES FOR HIGH PRESSURES."

W. A. BLANCK:—The superiority of oil switches over air-break switches for high-pressure work, in so far as it relates to reliability of operation and line disturbance, is very well recognized, but still there are many cases where the much-abused air circuit-breaker in the form of a fuse breaking under oil or a lead fuse in connection with a spring-operated lever is the only device suitable to be installed.

In the case of a high-pressure transmission line passing a mining district, where the customers are usually widely scattered over the territory, and sub-stations with static transformers of less than 100 kw. capacity are often required, it is evident that an automatic oil circuit-breaker in a brick compartment would involve nearly double the investment of the transformer.

But as a matter of fact the high-pressure tap to the transmission line will be interrupted only in case of a breakdown of the transformers, since all secondary shorts or overloads are limited by properly dimensioned secondary fuses, so that the action of the air circuit-breaker, installed in connection with a set of disconnecting switches, is only called for in utmost emergency.

JAMES LYMAN:—In most cases the source of current supply for operating oil switches is a storage-battery, and wherever it is used it has proved a very reliable source. It is very seldom that an automatically operated oil-switch fails.

P. JUNKERSFELD:—He believes that although switches are carefully built and located in the station, but little thought is given to the arrangement of the connections. This should not be the case.

DISCUSSION ON "TERMINALS AND BUSHINGS FOR HIGH-PRESSURE TRANSFORMERS."

W. G. CARLTON:—The speaker desired to know if any one present could state whether or not there are any 80 000-volt lines in operation.

E. O. SESSIONS:—In California the lines are operated from 45 000 to 60 000 volts, depending upon the reactance in the line.

P. JUNKERSFELD:—In a very large proportion of high-pressure work oil-switches play rather an important part. One question of importance is the building of suitable doors for oil-switches. The question has been discussed in different parts of the country as to what is the best and most satisfactory door for an oil-switch compartment. The glass door and wire glass door can readily be seen through for inspection purposes. While with the iron door or with the Alberene or slate slab you cannot readily inspect, and are liable to use the switch when it is not in order. Alberene slabs and iron doors can not be so easily and safely removed as glass ones and consequently the switches are not so frequently inspected as they should be.

G. N. EASTMAN:—One instance might be cited where a company operating in Chicago had a solid door and for some reason the oil suddenly disappeared from the oil wells. There was only a slight indication of this from the oil on the floor outside. The switch, however, operated satisfactorily on closing, but not so well on opening the circuit. When the doors were removed it was seen that there was considerable oil inside the switch.

W. G. CARLTON:—The speaker thinks the amount of wood in the frame of the door is not enough to cause much fire. There is practically an equal amount of inflammable material close to the switch in the insulation of the leads. In operating a number of lines on one bus-bar, when several switches open up due to trouble, it is not always possible to tell on which line the trouble is. If the oil-switch opens up a line on which there is a short circuit, some oil will generally be thrown from the switch. With a glass door the attendant can see where oil has been thrown out of the switch and thus save time in locating the trouble, as has been proved by experience in a number of cases. There is the possible objection of breaking the glass, but there is not much fire-risk with the amount of wood available.

I. E. BROOKE:—In the construction of some oil-switches it seems as if an iron door comes rather close to the live copper, and that the liability of grounding on the iron door would more than overbalance the objection to the fire element on a wooden door.

MR. THOMAS:—The speaker believes it has been the practice to ground the framework of the oil-switch as well as the door. He approves of it and considers that everything in the shape of framework on a switchboard should be grounded.

P. JUNKERSFELD:—One point particularly has been brought out in connection with oil switches, and that is that they need a great deal of attention. A switch is looked upon as something which can be operated occasionally and then left alone; but that is not the case with an oil-switch. It must have frequent and good inspection, and in order to get good inspection it must be arranged so that the operator may easily see its condition. One of the speakers has made the suggestion to have an iron door which would open outward and downward. Why does he say you get better inspection when a man opens an iron door than when he looks through a glass door?

E. O. SESSIONS:—The speaker has used wooden doors with glass windows for the switch-cells, but they were replaced by iron doors, about eight and a half inches away from switch-tank with a two-inch air-space all around the door, on account of the destruction of the wooden ones.

P. JUNKERSFELD:—Glass doors of heavy plateg-lass in three sections, which will enable every part of the switch from the bottom terminal to be seen, have been in service for some time.

W. G. CARLTON:—In the case Mr. Sessions mentioned of the glass door being blown off, why would not the same thing happen to an iron door? also trouble has been caused by switches grounding to an iron door.

E. O. SESSIONS:—With wooden doors the case was fitted tight, while about the iron doors there was left a two-inch space. With glass doors after one blowout of the switch, the glass would be so obscured that it would be impossible to note what happened without opening the door, but arranging the iron door so that it lacks two inches of closing will permit the inspection of the switch.

R. F. SCHUCHARDT:—To illustrate the point brought out by Mr. Brooke, the speaker cited the following case: An oil-switch had opened on a very heavy overload and some of the porcelain posts were so badly broken that one of the oil-wells fell forward. After the switch was opened the lower part connected to the oil-wells was still alive and if this well had fallen against an iron door thoroughly grounded, the resultant short circuit would certainly have caused great damage. With a wooden door with a glass front no live parts could come in contact with metal.

E. O. SESSIONS:—In the Waterside Edison station in New York all the doors are made of soapstone, or Alberene, as it is called, and are fitted in close against the brickwork.

EDW. SCHILDHAUER:—If Mr. Session's advice is followed to erect the door two inches from the brickwork, the fire-proof advantage of the iron door is *nil*. It would look rather odd to see a brick switch compartment lined with Alberene stone on three sides and equipped with an iron door on the fourth or front side, while the distance from the oil vessel to the door is the same as to the Alberene. If an oil vessel bursts with

enough generator capacity back of it, the speaker believes that there will be in most cases very little left of the iron door.

P. JUNKERSFELD:—The large companies in Chicago have had some oil-switches in operation for a number of years; in fact, some of the first hundred switches that were made for the Metropolitan station in New York, which was the first extensive installation of the compartment-type of switch, were shipped to Chicago. The first had the asbestos and iron doors, then followed Alberene doors, and more recently the advantages of the glass door appeared. One or two experiences brought out very forcibly that it was desirable to have a glass door and at the same time a fire-proof door. That, of course, meant a metal casing. After that, however, it was realized, as Mr. Carlton pointed out, that what little wood is introduced does not seriously diminish the fire-proof character of the door and does not increase the danger. The fire-proof barriers between the phases are really depended upon to prevent trouble. It is not often that the switches are gotten close enough so that anything thrown out at the front would be a serious matter.

G. N. EASTMAN:—Some five years ago, when the question first came up about using oil-switches in preference to air-switches, he made some tests to determine what the relative rise in pressure in the cable would be upon opening the circuit. He found that in a three conductor No. 00 cable three miles in length, the changing current was great enough so that upon opening the circuit with an air-switch, the arc could be gradually drawn up, and an increase in pressure of 50% "noted by a static voltmeter" could be obtained. If the switch was opened quickly, using a single break in the oil, no increase in pressure could be noted. Drawing the arc out in the oil a rise of from 10 to 15% was obtained. By connecting four breaks in series in oil it was practically impossible, under any conditions, to obtain a rise in pressure.

The speaker believes that upon opening a short circuit the tendency of the arc to hold would be reduced by having breaks in series. With some conditions, it is only by holding the arc—"the arc acting as an interrupter"—that you obtain a rise in pressure. The rise will be more severe with a short circuit under certain conditions than with only the charging current.

MEETING AT PITTSBURG, APRIL 7, 1904.

Discussion on "The Relative Fire-Risks of Oil- and Air-Blast Transformers."

J. W. Farley:—For fires inside of transformers themselves, a chemical extinguisher can be used to good advantage. If a flash should occur inside the transformer, and ignite the oil which has soaked up on the insulation on the leads, the fire can be put out with ease by means of an extinguisher, which will be very effective even if the surface of the oil is actually burning.

Light brick walls may be built between the different transformers and low deflecting walls may also be arranged so that in the event of an accident to the transformer case, due perhaps to the falling of a beam or tile from the roof at the time of a fire, the escaping oil would be prevented from spreading over the premises and would be diverted either into a sewer or out of the building at some point where it would do the least damage. It is always a good plan to pipe from the transformer cases to a storage-tank or to a pit or sink-hole located in the most advantageous place, in order that in time of emergency the oil may be withdrawn from the transformers.

One field for the air-switch is its use for high pressures, where the amount of power is not very great. Under these conditions the air-switch will act just as satisfactorily as an oil-switch and often is very much cheaper than the latter. This is particularly true for pressures between 20 000 and 40 000 volts, and where the amount of power available on short circuit is comparatively small, as at the end of a transmission line at a sub-station with an output of 600 or 800-kw. Air-switches can easily be installed and at a cost probably not one half that of installing oil-switches.

Regarding the relative amount of space required by air-switches and oil-switches, in a complete layout for a typical transformer station for a single-phase railway plant it was found that the use of air-switches made just as compact, if not a more compact, plant than could be secured with the oil-switches, as the latter needed disconnecting switches and series transformers for their operation.

N. J. Neall:—The speaker has noticed that in the West so much more account is taken of the ability of electrical apparatus as to afford continuous service than of its efficiency. One instance of what is now considered an old station has the high-pressure transformers in the main power-house only a slight distance from the generator. During an accident to the switching apparatus considerable burning oil was thrown out on the floor of the power-house; this heated up the transformer cases but did not injure the transformers.

Another plant visited had placed each transformer in a complete building by itself, the idea being that if one transformer

went out it would not communicate fire to the adjacent transformers.

A. B. BOND:—There is one point in connection with air-break switches which has not been brought out to-night and that is the question of thoroughly drying out the switch before its installation. Conditions sometimes arise under which the wooden parts of the conventional fuse-switch may become damp and thus introduce an element of danger to the attendants.

In a prominent Western plant considerable trouble was experienced with fires in the oil-filled transformers. The cases were perforated at the top, and it was found that by thoroughly caulking up all openings, the trouble from fire was eliminated. In this plant it was customary to use sand for fires in transformers. A patent extinguisher was also employed in which the novel feature of an interrupted stream was incorporated. With this extinguisher it was impossible for an attendant to receive a serious shock in consequence of directing the stream on live high-pressure wiring—a danger that exists where a continuous stream is used.

DISCUSSION ON "THE USE OF GROUP-SWITCHES IN LARGE POWER-PLANTS."

B. P. ROWE:—It appears that the use or disuse of group-switches is one which will be mainly decided from the station operator's standpoint. The fact that the Metropolitan Street Railway Company in their 96th Street and Kingsbridge stations and the Manhattan Railway Company in its 74th Street station are both in favor of using group-switches seems to indicate that there must be enough good reasons for using the system to overbalance the objections Mr. Stillwell mentions, and any others he has not mentioned. The speaker has noticed that other large stations beside those of the Metropolitan and Manhattan companies are being laid out with group-switches, and for large stations of this class, with a large number of feeders, there seems to be a decided sentiment in favor of using this type of switch.

In the first place, if a power station is a large one no one questions the advisability of using two sets of bus-bars. If every feeder must be capable of being thrown to either of the two sets of bus-bars, there are required three oil-switches to each feeder. If the feeders are grouped as Mr. Stillwell has described, the two switches which act as selector-switches for one feeder will, if large enough, be suitable to transfer a whole group of feeders. so that with a double-throw system, the group-switches, acting as selector-switches, are rather a saving in apparatus than otherwise.

But when a single set of bus-bars is used, with the ring system

and junction-switches, the group-switch is undoubtedly an extra to be considered, just as Mr. Stillwell has considered it. Such a case as this is the Kingsbridge power-station, where the group-switches were installed by the Metropolitan Street Railway Company, who already had had the experience of operating the 96th Street station to guide them, and considered them necessary.

Under such conditions, an arrangement of feeders is made, so that the opening of a group circuit-breaker does not shut down an entire sub-station. Mr. Stillwell presents a diagram which indicates that if the operator suddenly opens a group-switch in an emergency, to cut out a bank of six feeders, he thereby shuts down an entire sub-station. The arrangement the writer has in mind is to have one or two feeders from a group carried to one sub-station and the balance distributed to other sub-stations, so that each sub-station draws its supply of current through two or more group-switches. Thus the liability of shutting down sub-stations is not so great. The writer understands that the Kingsbridge and 96th Street feeders are connected in this way.

A point not brought out by Mr. Stillwell is that when a group-breaker is installed it must have a capacity sufficient to carry all of the feeders in the group and to open the total load under the worst conditions. Now if the feeders in the group are carrying large amounts of energy it is manifestly a more difficult thing to open it all on one switch than to divide the load and open it instead on the several feeder switches. In some cases it means a large switch and the amount of energy to be handled introduces an element which can hardly be neglected. There is obviously more liability that the large switch will cause trouble than any one of the smaller ones. In such a case a station operator would probably rather consider the group-switch an emergency-switch than to be habitually breaking large amounts of current on it to save time in transferring feeders or cutting them out of circuit.

This would seem to indicate that where feeders are of very heavy capacity so as to require large group-switches, they might be a source of trouble rather than a benefit unless they are reliable. Reliability is demanded because the group-switches are connected directly to the bus-bars. In the Kingsbridge power-station the opening of the group-switch automatically opens all the feeder-switches connected to it. This insures that there shall be two breaks in the circuit and might help out the group-switch.

MEETING AT PHILADELPHIA, MAY 9, 1904.

Discussion on "The Use of Group-Switches in Large Power-Plants."

H. F. Sanville:—For an important installation, which must consist of a large number of feeders all of considerable energy capacity, the extra expense of the additional switches is warranted. For such systems as the Manhattan, New York Edison, Metropolitan, and Rapid Transit in New York, it is almost, if not quite, necessary to adopt the group arrangement. In these systems each group runs to a separate substation, so when a station is shut down it is possible to test the mechanical operation of the mechanism from the controlling panel without any interference with service and without opening the lever disconnecting switches.

The necessity of the group-switch in series with the feeder-switch was a development of the uncertain operation of oil-switches under emergency conditions. It has since been found, however, that the switches are extremely reliable and will rupture circuits carrying almost unlimited amounts of energy.

The high rupturing capacity of the switches makes it desirable that the group-switch be made automatic only through a time-limit relay, which will allow a defective feeder to disconnect itself from the group bus-bar without necessarily shutting down the entire group.

By the proper arrangement of controlling switch circuits reduction of load can be readily made without the use of a group-switch and the load may also be transferred. In some installations a sectionalized ring bus-bar automatic switch has been used in place of group-switch.

Discussion on "Oil-Switches for High Pressures."

H. F. Sanville:—Recently a series of tests of oil switches were made including over 1000 records of currents from short-circuited alternators varying from two 300-kw. machines at 13 000 volts to a generator capacity of three 3750-kw. machines at 2200 volts, including also a number of tests at 75 000 volts. It is almost invariably the rule, as shown by the records, that the circuit opens at or near the zero of the wave, in almost every case the circuit opens on three consecutive zeros in the three phases; fewer than 10 exceptions to this were recorded. In the exceptional cases the current of one phase holds for one or two cycles beyond the first one to rupture. It may be of interest to state the conditions of some of the short circuits which have been successfully opened by oil switches during the last few years.

1. Seven 5000-kw three-phase, 11 000-volt generators on the Manhattan System were connected to the bus-bar. A short circuit occurred within 300 feet of the station, the

automatic switches opening without difficulty. There were at this time some coincident cable breakdowns, due probably to the resonant effects set up by the enormous arc at the subway junction box where the short circuit occurred. Since that time a steel tape has been used at the cable connections to prevent a short circuit developing an air arc.

2. *New York Edison System.*—Seven 3500-kw. 6600-volt generators were on one bus-bar and four on a second. A connecting switch was accidentally thrown in with the bus-bars out of phase, the oil-switch ruptured the circuit without causing any disturbance to the system.

3. *Niagara Falls.*—Five 5000-h.p. generators on the bus-bars stepping up through 25 000-h.p. transformer capacity to 22 000 volts on the Lockport feeder. A short circuit was made by a wire thrown across the transmission line and the circuit was successfully opened by the oil switch on the high-pressure side.

4. *Niagara Falls.*—In power house No. 2 of the Niagara Falls Power Co. two weeks ago, a short circuit developed on the 11 000-volt feeder running to the Canadian side with seven 5000-kw. generators on the bus-bar. The cables made a peculiar rattling sound from the movement of the insulators, but no damage was done the circuit being opened without any disturbance of the system by the oil-switch on the 2200-volt feeder to the transformer house.

5. Some time ago some short-circuit tests were made on the 33 000-volt system of the Aurora, Elgin, & Chicago Railway Co. These tests were made single phase and three phase at the main station and also at the Warrenville sub-station at the other end of the line. The circuits were opened without difficulty by the oil switches; then the switches were made double-break for opening the three-phase shorts instead of three breaks; *i.e.*, the middle leg of the switch was short circuited, but no difficulty was experienced in opening the circuits.

6. In another test a 2500-kw., 2200-volt alternator was excited to 2500 volts and stepped up to 75 000 volts by three 750-kw. transformers, giving a total transformer capacity of 2250 kw. The standard 60 000-volt oil-switch operated as a single-break switch by cutting out one row of pots, opened three-phase short circuits without the slightest difficulty.

W. C. L. EGLIN:—Most of the difficulties in the use of oil-switches are not in the electrical but in the mechanical features. The clutches between the motor and the switch mechanism, and the devices to maintain the switch either in its open or closed position, have been responsible for most of the failures, necessitating frequent inspections and adjustments of these parts of the switch. Proper alignment of parts, rigid construction, and ample capacity in clutches, with stops arranged to hold positively the switch in an open or closed position are essential to the satisfactory operation of an oil-switch.

The care of the oil is very important. After the oil has been in use for some time, it will deteriorate, due to the operation of the switch and to the collection of foreign material in the oil. Care must be taken to prevent water from mixing with the oil; the oil should be completely changed at regular intervals, and means be provided to keep the oil clean. In one case of failure of an oil-switch the current jumped a distance of half an inch in the oil, and punctured the fibre lining of the oil case. The oil was examined and there was found sediment of dirt and dust at the bottom of the oil tank. This switch had been cleaned within six months.

BLANK
PAGE

A paper presented at the 186th Meeting of the American Institute of Electrical Engineers, New York, April 22, 1904.
Copyright 1904, by A. I. E. E.

THE MECHANICAL CONSTRUCTION OF REVOLVING-FIELD ALTERNATORS.

BY DAVID B. RUSHMORE.

INTRODUCTION.

The mechanical design of alternators is undergoing rapid evolution. Among the first commercial machines in this country were the generators with stationary fields of cast iron, the yoke and poles being cast together. The armature had a smooth core and carried surface-wound wire in the form known as the " pancake " coil. The common frequencies were from 125 to 133 cycles per sec., and outputs ranged from 25 to 200 kilowatts; all the machines were belted.

On account of the small amount of wire carried, these machines had excellent regulation; the flat coil gave a nearly perfect sine wave. The single-phase reaction—for polyphase currents were not then in general use—caused the solid poles to heat; and the relatively large number of poles of uneconomical section, together with the large mechanical clearances, made the machines heavy and costly. The armatures were hand-wound and the windings were often entirely destroyed by striking the pole-pieces, due to wear of bearings, or by a piece of metal falling on the armature.

The next step was to laminate the poles and to cast them into the yoke; the armature was made iron clad, with one large tooth per pole and the machine-wound coils were drawn up under the projecting tooth-face and held in place by wooden wedges between the coils in the same slot. Mechanically, this machine was a great improvement; the regulation and wave-form suffered greatly and soon the armature was changed to a many-slot distributed winding, at about the time when the use of polyphase currents was becoming general. With various small modifica-

tions this machine was standard for some time, until higher pressures and increased outputs made it desirable to revolve the field instead of the armature. Increasing sizes brought about the development of the " engine-type " generator, in which the revolving field was mounted on the engine-shaft, and for the past few years this has been the standard type in this country.

Generators driven by water-wheels have always been special, when direct-connected units have been used; the alternator is designed to suit the speed of the water-wheel, which in turn is determined by the type of wheel, the outputs and the head of water.

The indications are that the greatest development of the alternator driven by the steam-engine has been reached and that in the immediate future such units will be driven by steam-turbines and to some extent by gas-engines. It seems proper at this time to bring together in one place illustrations of present practice in the mechanical construction of engine-driven, revolving-field alternators, together with the development which has already taken place in turbine-driven sets. There is, to the writer's knowledge, no place where such information can be found; much of that given here has never before been published, and descriptions of foreign machines are scattered among so many sources as hardly to be available for American engineers and students. Discussion of the inductor alternator, except for a few minor details, has purposely been omitted. A special description of this excellent machine will be given later elsewhere. With this exception, the intention has been to illustrate modern practice as completely as possible, without including curiosities. Electrical and mechanical design are so closely related that a discussion of one necessarily involves the other; commercial designing involves such broad considerations of all factors of labor and material, as well as technical electrical points, that mechanical considerations, instead of following the electrical calculations, must now often precede them.

The prices of material and the cost of labor vary at different times and in different countries. The best designs of machines must, therefore, vary. The same specification can often be met by two radically different generators. Commercial considerations often limit designs, especially from the point of utilization of standard frames and parts. The factors of output, frequency, phases, pressure, regulation, heating, and efficiency are so closely related, that if one or more of these be fixed, the others can be varied only within limits. As all losses result in heat, which must

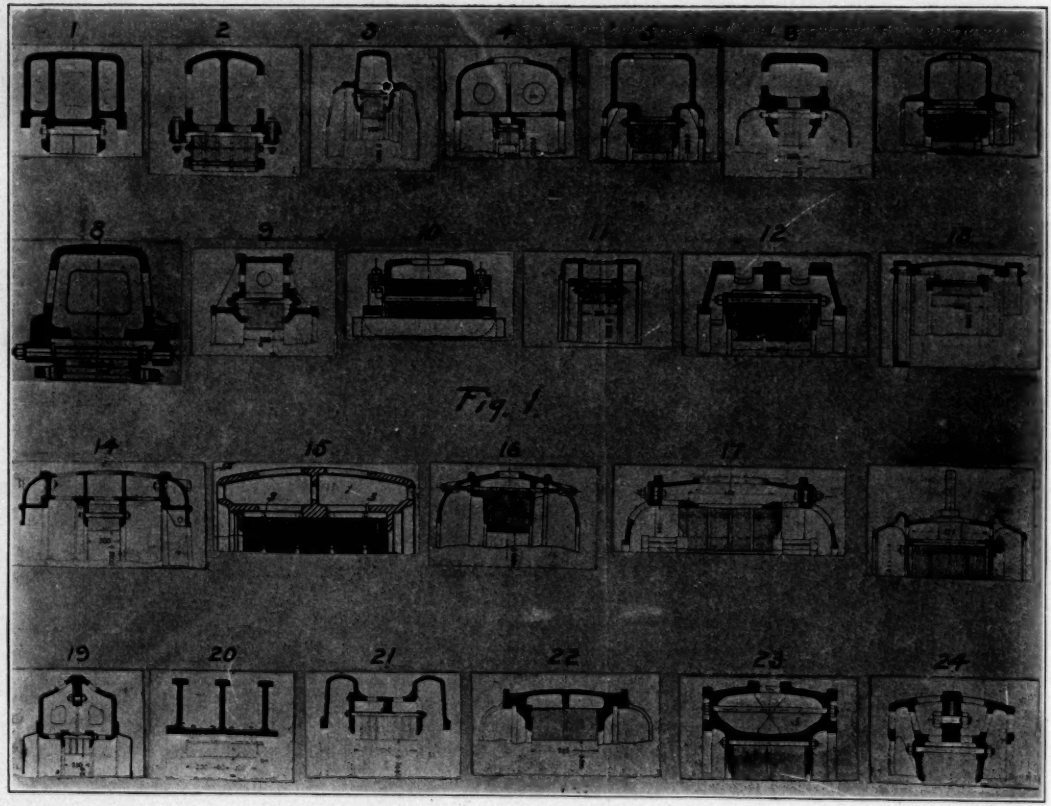


Fig. 1. Yoke-Sections.

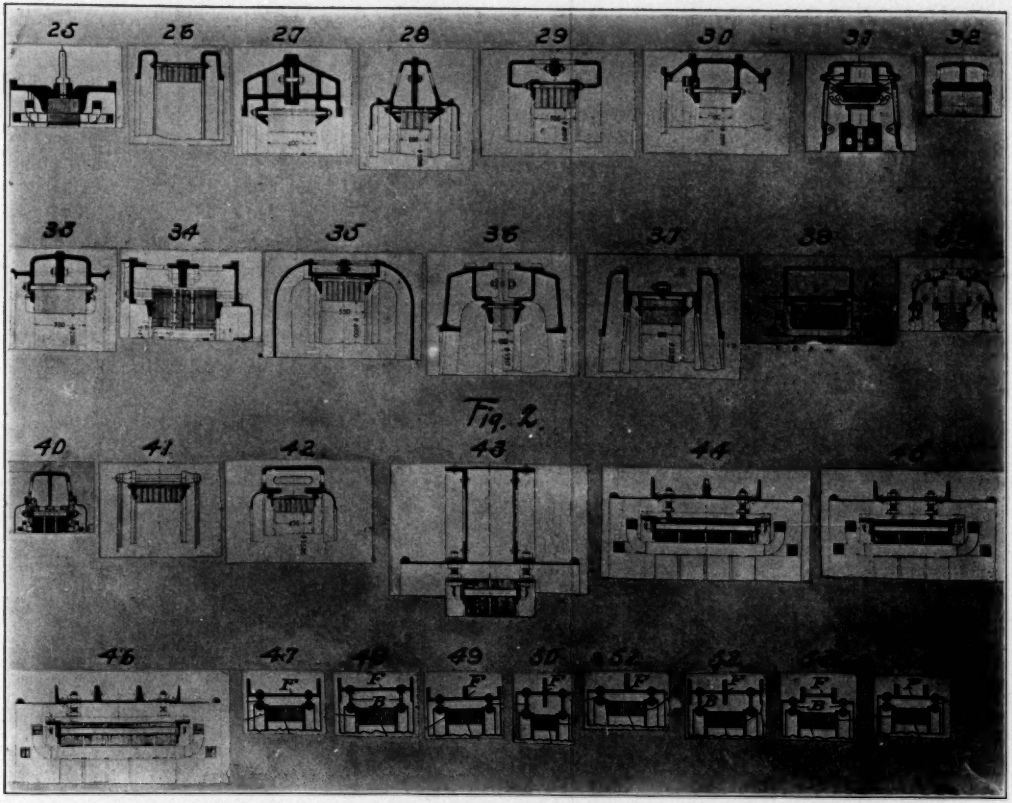


Fig. 2. Yoke-Sections.

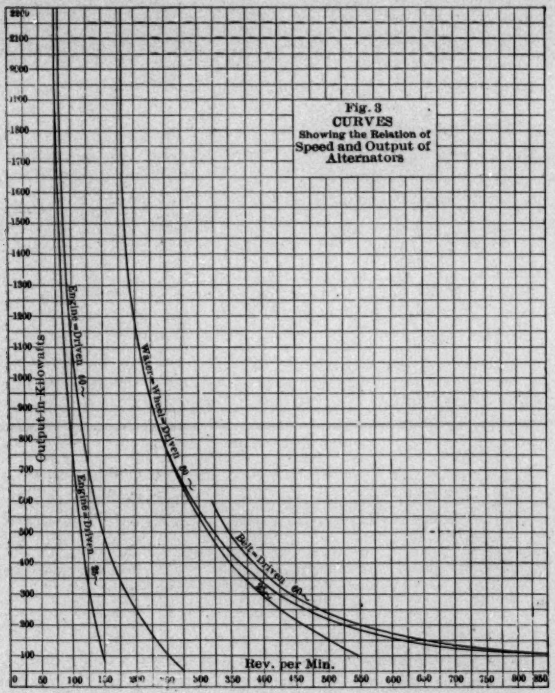
be radiated from a surface determined in part by magnetic considerations, the questions of heating and efficiency are closely related. The smallest gap being fixed by mechanical reasons, there is a minimum value to the kilowatts per pole which can be economically used. If other factors remain constant, we cannot save in weight of active material by increasing the speed of revolution unless we, at the same time, increase the peripheral velocity, which may not be possible. To some extent regulation and efficiency are incompatible; cheap electrical designs may necessitate expensive mechanical features. These are but a few of the items which indicate how broad a view must be taken in designing alternators. In most machines of to-day, it is usual to work out a preliminary electrical design; the mechanical features are then developed, and the necessary modifications are then made in the original calculations.

YOKES.

The yoke or armature frame is one of the most important mechanical parts of the engine-driven alternator. Its object is to support rigidly the armature laminations and winding while affording good ventilation and giving an artistic appearance to the machine as a whole. The commercial object of course is to attain this end with a minimum of labor and material; to this end a large number of different designs have been made, some of which are shown in Figs. 1 and 2. For the past decade the output of single units has increased rapidly, while the speed for large sizes has remained fixed at 75 rev. per min. The outside diameter has thus increased constantly and with it the difficulty of proper yoke-design, without excessive weight. Probably the maximum diameter has already been reached, for with the introduction of turbine-driven alternators, the sizes of machines for the same output are very much reduced. The speeds of various types of alternators are shown in Figs. 3 and 4.

While there are many different yoke-sections, there are but few different types; first, there is the cast-iron box-section, in which the frame is divided horizontally, forming a beam or arch supported at each end, uniformly loaded; the greatest moment of inertia, with the least weight, is aimed at; the outside of the shell is well rounded to give a finished appearance. The expensive patterns formerly necessary are now dispensed with by "sweeping-up" the mould. Air-gaps or mechanical clearances vary from 0.125 in. to 0.75 in. in engine-driven machines, hence any appreciable

deflection of the yoke would be inadmissable. The deflection of the yoke is due to its own weight as well as to that of the laminations, winding, etc.; in order to provide for wear in the bearings it is usual to set the revolving field high, which brings an additional stress on the yoke, due to the unequal magnetic pull.



Large boring machines are usually horizontal, so it is apparent that the geratest care must be used in machining the frame in order to allow for the deflection which will be found under conditions of service. With this style of yoke, the feet on which the frame rest are sometimes given a pressure toward

the centre and the lower part of the frame is supported by jacks at one or more places. If alternate layers of laminations are lapped and strongly clamped together, the friction between plates gives them a resistance against deflection, which may be considerable; if the laminations are firmly dove-tailed into the yoke, the

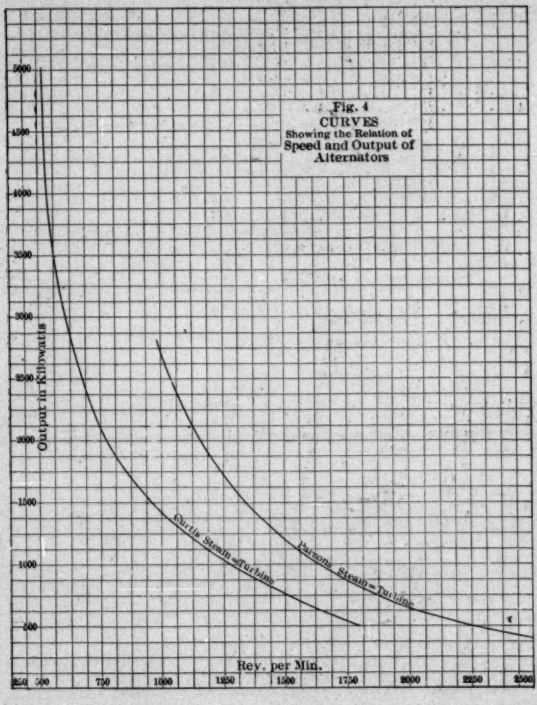


Fig. 4
CURVES
Showing the Relation of Speed and Output of Alternators

resistance is still further increased. It is customary to arrange for sliding the stationary armature on the base, in order to gain access to the windings and poles. The standard form of cast-iron yoke is shown in Fig. 5.

Where the cast-iron yoke is divided vertically, each half of the

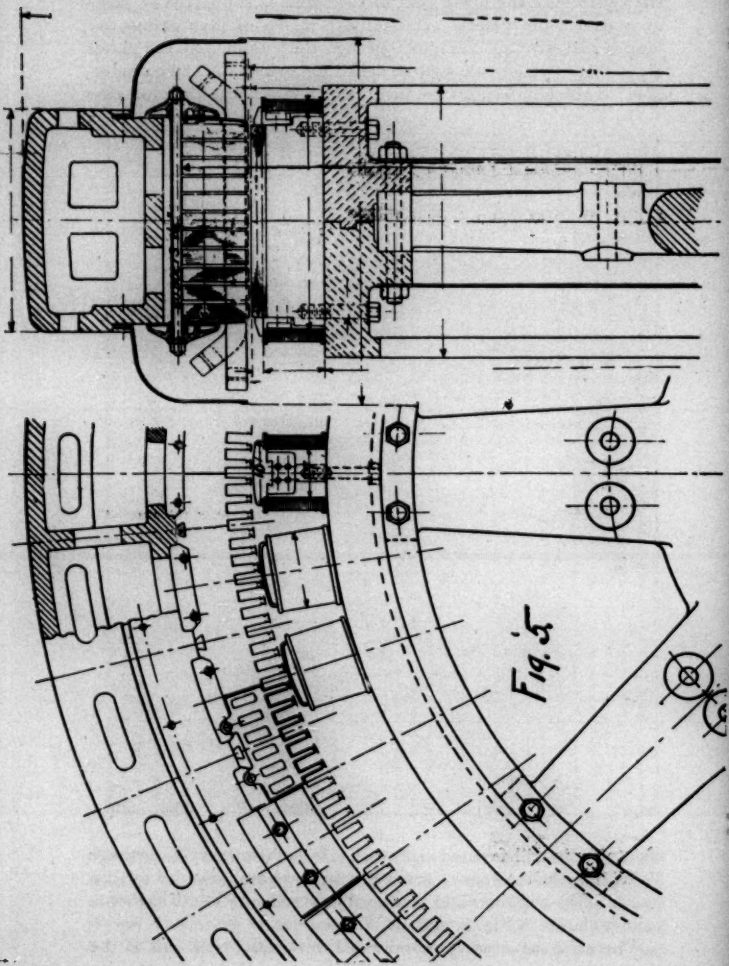


Fig. 5

frame is constructed as a cantilever, growing smaller in section toward the top. With this construction, in which the machine is supported at the bottom, more difficulty is experienced in preventing vibration; there is here no base for yoke and bearings, which are supported on independent foundations. Access to the winding is had by sliding the armature back from the shaft. When it is desirable to do so, for reasons of transportation or otherwise, the frame may be subdivided into more than two parts.

In some cast-iron box-sections such as are shown in Nos. 26, 27, 28, 29, 33, 34, etc., the frame is divided by a plane perpendicular to the shaft. The clamps for the laminations are cast on the frame and the active iron is held by bolting together these parts.

Another type of box sectional construction, illustrated in No. 35, has been used by Brown Boveri & Co. The frame is light and is supported mainly by flanged arms, which join all parts of the circumference to a ring supported on a trunion surrounding the bearing. In place of the usual foot there is a screw for preventing rotation of the armature, and when this is removed the whole frame may be revolved upon the trunnion bearings. This design gives a light yoke-section, and thus a light machine; the armature is difficult of access on account of the number of arms, and it is not easy to provide for wear in the bearings. When properly erected this construction should be very firm. In some cases instead of channel-arms, rods have been used; but they are liable to vibration, if long. The construction of this type is illustrated in Fig. 6.

A large variety of box and shell cast-iron sections are possible, as shown. These vary in minor details, but all perform the same general functions. A modification of the box-section is that in which a small box is stiffened by wide rings, which are made removable; one ring may be cast with the box-section. Yoke No. 41, illustrates a distinct type, shown more clearly in general construction in Fig. 7. In this the non-active metal is reduced to a minimum. The frame is braced by two sets of tie-rods, forming chords, which connect to rods passing through or just back of the laminations; instead of the box-frame we have a single cast ring on each side of the active iron. It is claimed that in large machines the weight of the frame can be made less than one fifteenth that of the box construction. A modification of this type is to make tangents of the tie-rods instead of chords; the ends of these rods are

fastened to pivoted arms in the vertical plant of the laminations; the rods are drawn up when cold and as the machine heats the desired stress is brought upon them. These constructions, which are the inventions of Mr. Lasche of the Allegemeine Elektricitats Gesellschaft of Germany, offer many advantages from a manufacturer's point of view. With the exception of the end-rings, which may easily be kept in stock for different diameters, the

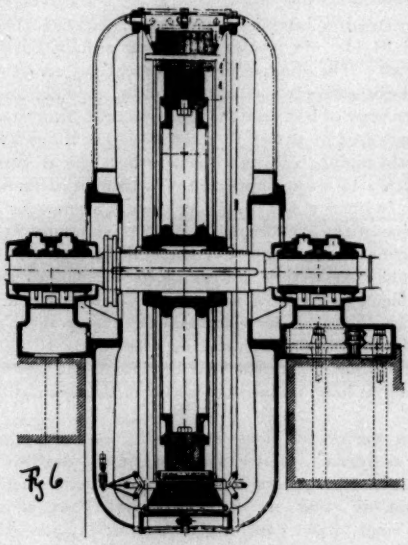


FIG. 6. Frame of Brown, Boveri & Co.

remainder of the material is easily adapted from supplies which may be kept on hand, and machines of any diameter or practical length may be quickly manufactured, as the long waits incident to pattern shop and foundry work are eliminated. The laminated iron is well exposed to the air and the ventilation is excellent which should, where the larger part of the heating is due to iron loss, result in a better utilization of material. The light construction would be liable to vibrate with large diameters, and the rough

appearance has been the subject of criticism, as well as the lack of protection to the winding.

A third distinct type is shown in yoke-section No. 43, various modifications of which follow. In this the supporting section,

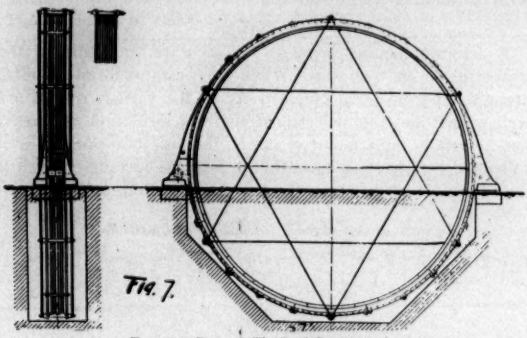


FIG. 7. Braced Tie-Rod Construction.

instead of being a cast ring, is constructed of rolled plate and angle-iron. The laminated iron is built up separately and is then placed in the casing and held in position by bolts. This is shown clearly in Fig. 8. Yoke sections No. 43 to 54 show differ-

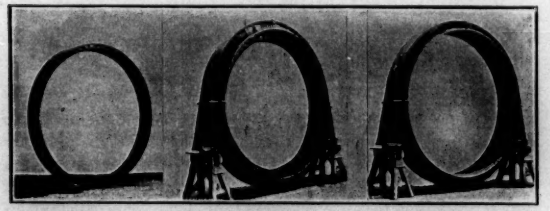


FIG. 8. Rolled Plate Box-Yoke.

ent frames built up in this general manner. The strength of the supporting structure is obtained with light weight and a minimum material; the electrical part is well protected and it is not necessary to bore out the frame as with the cast construction. The ventilation may be made good, and the appearance is pleasing. In this construction a considerable amount of labor is required in

bending and fastening the plates and angle pieces composing the frame. While the cost of material may be small, the cost of labor will be high." There is at present no construction more satisfactory for large machines than the cast-iron yoke of box-section with laminations held by dovetails.

Laminations.

A designer requires primarily an accurate knowledge of the properties of his materials. While the constants for mechanical strength and electrical conductivity of the various metals are well known and the dielectric strength of insulation requires a not unusually large factor of safety, the magnetic properties of rolled-steel plate are not controlled with the certainty which is desirable. Much has been done in this direction, and the solu-

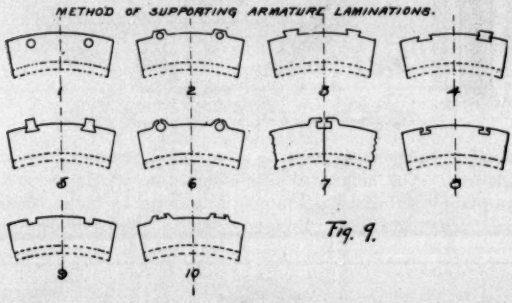


Fig. 9.

tion of this problem is now being sought by many minds. Guarantees of heating and efficiency are largely dependent upon the iron-loss, and any uncertainty regarding this demands a greater margin than otherwise would be necessary. In the tests which are always made before iron is used, the results may vary less than five per cent for a considerable time, when some iron may be received with several times allowable loss, which, so far as is known, has received the usual treatment. The hysteresis loss may increase with time, an effect called aging; to prevent this certain chemical composition and treatment is necessary. In order to reduce this loss, iron must be annealed at a high temperature after rolling; this is sometimes done after punching and sometimes before; if done after punching, the shape of the plate

may change, and filing of the slots may be necessary to a considerable extent; when annealed before punching, difficulty may be experienced in working with a soft metal which drags on the edge of the die, especially with thick plates, and the lamination is thereby hardened for a short distance on the edge.

The thickness of rolled plate for armature work is 0.014 in., or 0.018 in., and for field punching may be as thick as 0.062 in., or 0.125 in. A cubic inch weighs a little less than 0.280 lb. Insulation separating adjacent sheets may be japan, a silicate preparation, or thin paper. The space occupied thereby is about 10% of the apparent section, but this varies with the thickness of plate; the section used is of peculiar form and from 20 to 60% of the original sheet is lost. The construction of dies

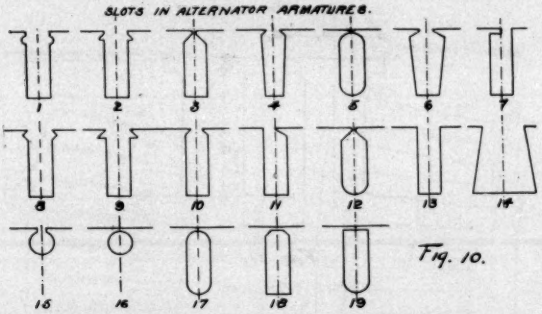


Fig. 10.

necessitates that the length of lamination should not be much greater than 24 in., and complete form may be punched out at once, or by using blanking and slotting dies, in several operations.

Wrought iron has been almost entirely superseded by steel for armature plates; the steel is made by the open-hearth process, either acid or basic, and limits are set to the allowable percentages of carbon, manganese, sulphur, phosphorus, and silicon which may be present. The combined iron-loss per pound for a certain thickness of sheet at given frequency and density is limited, and also the percentage increase of this loss under continued heating at a fixed temperature for one month.

Supports for Laminations.

If the alternate layers are lapped and the clamps drawn to-

gether with a strong pressure, the laminated ring will be self-sustaining. It is, however, necessary to support the active iron from the yoke by one of a number of possible methods; those in common use are illustrated in Fig. 9. The laminations may be supported on bolts or rods, the ends of which are held by the frame. Nos. 1, 2, and 6 show variations of this kind of support; first, where the rod passes through the active section; secondly, where the laminations project back for the bolt-hole, and a modification in No. 6 which prevents the active flux from cutting the bolt. This manner of supporting the iron is economical and satisfactory on machines of certain dimensions. If the density in the armature core is high, No. 1 should not be used; with a considerable length of armature core and especially with much

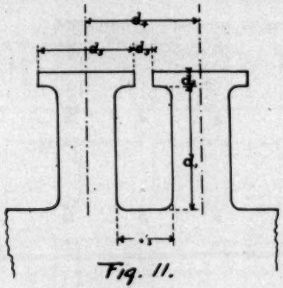


Fig. 11.

Slot Inductance.

radial depth of iron, the surface of the core may bulge or the size of the bolts to prevent it may become excessive. Insulated bolts may be used but as a rule are undesirable from a mechanical standpoint.

No. 3 is a very satisfactory method for use with a cast-iron yoke. Dovetails are cut in the frame, parallel to the shaft, and into these corresponding projections on the laminations are fitted; this makes an absolutely reliable method of retention; somewhat expensive, but suitable for the largest machines. Instead of the preceding, a key may be screwed to the frame as in No. 4, which gives results similar to the dovetail and offers several constructional advantages.

No. 5 shows a method where the key-seat in the frame is straight and the key used only for alignment. A driving fit

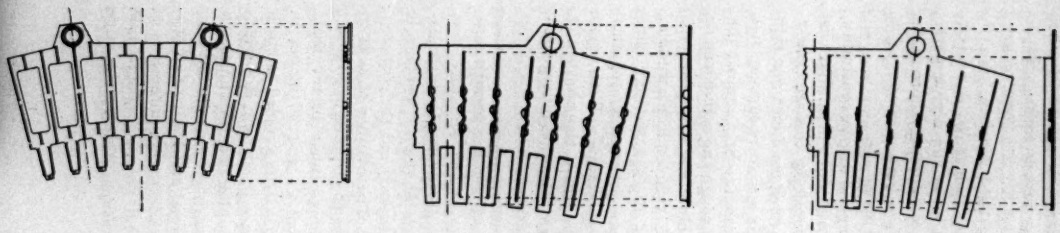


FIG. 12. Ventilating Space-Blocks.

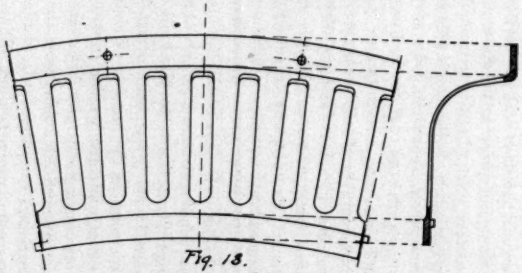


FIG. 13. Shield for Protecting Armature Coils,

holds the key to the frame, while reliance is placed on the friction between plates and keys to keep proper form. No. 7 shows a peculiar method used abroad, and No. 8 a form of key used on small machines and for holding light weights. No. 9 is simply an aligning key, and No. 10 the same as No. 4, except that the key is in a projection instead of in the active part. Where the support is back of the core-section proper, more plate is required but less loss occurs in the bolts or keys.

Clamps for Laminations.

In order to prevent humming of the iron and to give continuity to the magnetic circuit, it is necessary to clamp the laminations under considerable pressure. Methods for doing this are clearly shown in the sheet of yoke-sections. In most machines, one side of the frame projects nearly to the inside armature surface, and the other side, which is removable, is drawn tightly against the laminations by bolts which pass either through the active iron or immediately behind it. In some machines the clamping projections are both cast on the frame which is parted in the middle; both rings may be removable. Instead of rings, we may have a large number of small retainers which are either drawn together by bolts or each is fastened directly to the frame. With small radial depth and small length over laminations, the problem of properly clamping the iron is simple, but in machines of large output and low frequency much care is required.

Slots.

In the early days of the " pancake " coil and the smooth core, the winding was placed on the surface of the armature, but present practice is to place all coils in slots. To do this satisfactorily the shop work must be carefully done. The die is expensive, as the number of slots is increased, and the cost may be much affected by the form of slot. The number of slots in the punchings is preferably even to make the lapping of adjacent sections possible, otherwise the punchings must be reversed; punchings are preferably made between 24 and 36 inches in length for large machines; filing of slots is to be avoided as much as possible, hence an additional allowance is made in slot-width which becomes more important as the number of slots is increased and their dimensions diminished. Electrical demands are conflicting; economical utilization of material and low cost of production demand few and large slots, while the requirements of heating and regulation call for many small ones. A general rule of electrical design is to avoid concentrations of magnetomotive

forces and of sources of heat, while opposed to this, are the best conditions for manufacture; hence the result therefore is always a compromise. Where the slots are large and wide, and especially if the teeth are narrow, the reluctance of the path of magnet flux varies, introducing harmonics into the e.m.f. wave, and causing vibration of the teeth; this, in certain cases, has broken them off. A sharp corner to the pole-piece accentuates the trouble; with solid pole-faces, the ratio of gap-length to slot-width must not be less than a certain figure, or undue losses and heating will occur in the pole-shoes; under the same condition, copper damping devices cannot be used close to the armature.

Slots may be punched in the armature at the same time that the lamination section is punched from the sheet; the lamination may first be blanked out and the slots punched one or more at a time on a special machine, or the plates may be built up into the armature ring and the slots formed with a milling cutter. The first and second are in use in this country, and the choice depends upon whether the number of plates to be punched will pay in the saving of labor for the greater cost of a complete die. The first method gives the best results; the second is apt to require more filing; the third method is foreign but is open to criticism because of the increased iron-loss which must result therefrom. It was used in the early days of railway-motor work, but has long since been abandoned here. Some of the machines at the recent Paris Exposition were slotted in this way. Fig. 10 shows most of the forms of slots in use at the present time in alternating-current machines; they may be divided into three classes: Open slots, partially-closed slots, and closed slots. The advantages and disadvantages of each are partly mechanical and partly electrical; open slots permit the use of machine-wound coils, which may be entirely insulated before being placed in position, a thin paper slot-insulation being used for mechanical protection. The insulation may be continuous; the filing of the slots need not be excessive. Coils are easily placed in slots or removed in case of accident and the self-induction of the slot is less. In certain cases small harmonics may be introduced into the wave-form, the excitation is greater for the same gap or we have a smaller clearance for the same excitation. Foucault losses may be produced in the pole-shoe or damping devices. Open slots are shown in Nos. 1, 2, 8, 9, 13, and 14. Partially-closed slots are of two kinds, those which may be wound through the opening and those wound from the end. Slots 7, 10, and 11

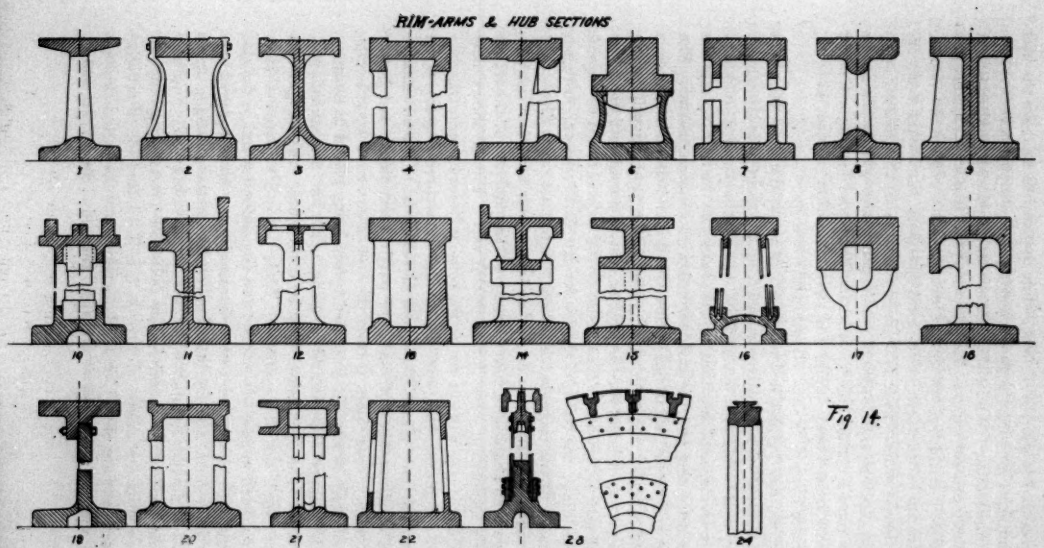


FIG. 14. Rim-Arms and Hub-Sections.

may be wound from the surface while such forms as 3, 5, 12, and 15 must be wound from the end. Where such slots are wound from the surface, a wedge is used and held in place by the projecting corners. Partially-closed slots require greater care in construction and render the problem of insulation more difficult than open slots. They decrease the gap-reluctance and the foucault loss in the pole-face while increasing the self-induction of the winding. The magnetic flux undergoes less variation and the clearance may be greater. Slot 10 may be wound from the surface where a heavy slot insulation is used sufficient to fill up the distance over which the corner projects. Slots 7 and 11 may be surface wound with two conductors, having a depth equal to that of the useful part of the slot, or with four coils or conductors per slot.

Where closed slots are used it may be assumed that labor is cheap and that wholesale manufacturing is not in vogue. The slots must be carefully filed if the space is well utilized; the insulation as well as the winding must be introduced from the end; in long cores this is difficult, especially where there are many turns per coil. In some cases with closed or partially-closed slots and a many-turn coil the latter is machine-wound and then cut, straightened, threaded through the slot and every turn separately soldered. With closed slots, the regulation is worse, and for standard guarantees the machine becomes very heavy. There appear to be no compensating advantages for this form of slot.

The closed and partially-closed slots prevent foucault losses in solid conductors; with open slots the bottom conductor may be made solid and the top one of cable if necessary, to prevent foucault losses.

To illustrate the importance of slot-shape on inductance and consequently on regulation, Fig. 11, showing a partially-closed slot is given. The inductance varies with the magnetic permeance (λ), where

$$\lambda = \text{Constant} \left\{ \frac{d_1}{3\,\omega_s} + \frac{d_2}{d_3} + \frac{2\,d_5}{\pi\,d_4} \right\} \times \text{length of iron core.}$$

Where the slot is round or where the corners are formed by quadrants of considerable radius, there is much less danger of insulation rupture due to the sharp bend.

Armature Winding.

The conductor used for alternator armature winding may be round or square copper wire, rectangular strip, or stranded cable. The cost of the generator is largely dependent upon the proportion of the slot cross-section which is occupied by active copper. There is a practical limit to the size of strip which may be used in the top of the slot and above which stranded cable is necessary. Cable has an effective section slightly over three-fourths of the apparent area, but with its use much less heating may result from the increased resistance loss than would come from the foucault currents induced in a solid conductor of the same apparent section. After manufacture cable is round but must be rectangular before it can be used, and must come very closely to gauge without being hardened in the process.

Where cable is used it is customary to give the coil a vacuum treatment which thoroughly impregnates all the interstices with an insulating compound. This removes all moisture and makes the coil solid and firm while entirely eliminating foucault losses. In some cases a solid conductor is used in the bottom of the slot and cable at the top.

Insulation is almost entirely an electrical problem, but one of the greatest dangers to which it is exposed is from vibration of the coil as a whole or of the individual conductors in the coil. For this reason, which explains the great advantage of the stationary over the revolving armature, the insulation should possess elastic properties. Coils must fit slots tightly and allowance must be made for a small decrease in size due to drying out under long-continued heating. With deep slots and narrow teeth the latter may vibrate slightly as each pole passes under them, and with very high-speed machines, especially those direct-connected to water-wheels, a certain vibration of the whole machine is inevitable. The end cross-connections must often be securely held for this cause as well as to protect against the bending action due to heavy short-circuits.

Ventilating Space-Blocks.

Some years ago a radical improvement was made in dynamo design by the use of air-ducts in the armature core. This has since been a standard method of construction for all cores whose length exceeds 5 or 6 inches. As heating is one of the principal limitations to the output of an alternator, the relation between the losses and radiating surface is most important; in direct-current work it is sometimes used as a starting point for the

design. It is usual to allow for effective radiating surface at least one side of the exposed iron in the duct, so it is easily seen that the radiation from the armature may be increased by the introduction of ventilating spaces into the cores, which cause but slight increase in volume or weight of the machine.

It is desirable that consistently-designed machines reach their limits of temperature and regulation at the same time. The external dimensions of the core are largely determined by magnetic reasons and the proper choice of number and size of air-ducts is therefore the point which largely decides the armature heating. In very small machines ventilating spaces have been made 0.156 in. wide; for most engine-driven alternators a width of 0.312 in. to 0.375 in. is used; in large machines of great radial depth of lamination, 0.5 in., 0.75 in., and even 1 in. ducts have been used; two spaces each of 0.5 in. are, however, preferable to one space of twice the size. The best width depends upon the depth of laminated iron, the peripheral velocity of the revolving field and the type of space-block used. The distance between ducts in core varies from one to three inches. Small ducts at frequent intervals help to reduce foucault losses; it is usual to place a space-block on each end of the core between the laminations and clamps.

The first space-blocks were made of brass or composition casting consisting of a solid flat plate with raised fingers on one side. The necessary thickness of the plate occupied half the distance between laminations and the blocks were expensive as well as inefficient. Fig. 12 illustrates some modern types; the first is a cast block such as it is desirable to use in certain cases, especially at the core ends; it is of skeleton form to give the least weight and to permit the greatest effective width of duct. The second type is the best construction; it is made entirely of steel; a plate 1/32 in. of thickness, of same form of armature lamination, has supporting pieces punched in, as shown, which in turn support steel fingers so formed as to be securely held in place. This construction is very firm and gives the maximum effectiveness of ventilating space, and without the introduction of non-magnetic material. The third type shown has the same advantages as the second with regard to space; the upright fingers are supported in a different manner.

Where the poles are laminated and placed close together, it is sometimes found desirable to have ventilating ducts in the revolving field-frame opposite to those in the armature; in some

foreign machines, ducts in the one are staggered with respect to those in the other.

Shields.

To give access to the armature winding it is usual to make the yoke-section so that all coil-ends and cross-connections are well exposed, an essential consideration from the standpoint of ventilation. To protect the cross-connections from mechanical injury, shields are fastened to each side of the frame, projecting out and over the cross-connections. These shields are sometimes made in a continuous ring and support the yoke. Many variations in form are found, but a typical modern design is shown in Fig. 13. The light iron casting is well opened to give good ventilation and is of such length as to be easily handled in assembling or making repairs; a minimum of machine-work is required; projecting lugs on the inner ends engage with adjacent sections securing accurate alignment.

Rims, Arms, and Hubs.

The fly-wheel is at times a part of the generator construction. At the higher frequencies the natural velocity of the revolving field approximates that which is used for fly-wheels and the two are often advantageously combined. At 25 cycles this does not give good results nor for direct-current generators, where frequency is much lower than 25 cycles. Fly-wheels are used for two purposes; *i.e.*, to give uniform angular velocity through one revolution and to give uniform speed over short periods of time. The usual specification is that the variation in angular velocity shall not exceed from 2.5 to 3 electrical degrees in one revolution; as the frequency and the number of poles is increased, the difference between the real and the electrical angle becomes greater, and the fly-wheel must be heavier.

With alternators the problem of the fly-wheel is almost entirely that of the requirements for parallel running; much has been written on this subject with but little of definite results. To give briefly the necessary relations, it may be said that in itself variation in angular velocity has but little to do with trouble in parallel running, except as it is related to other constants. The impulses from the piston give a frequency equal to the revolutions per second; the moment of inertia of the revolving part and the electrical constants of the machine give a natural period of oscillation; if these are equal we have the condition of resonance. It is necessary for successful work that they bear an approximately fixed relation to one another; it is also necessary

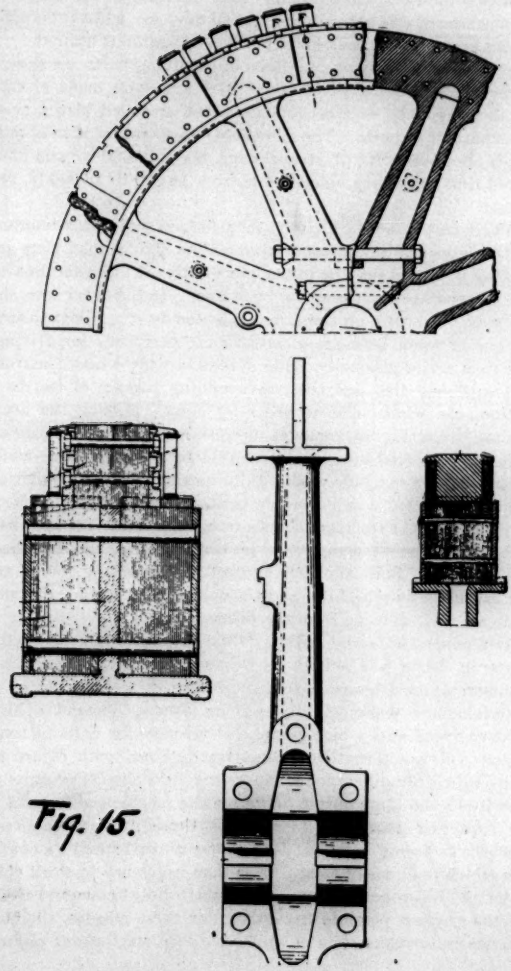


Fig. 15.

Fly-Wheel Type Revolving Field.

to have some electrical damping either inherent in the design of the machine or else obtained by special devices; when these conditions are observed, successful parallel operation is insured.

Sections of rims, arms, and hubs of revolving parts are shown in the accompanying sheet (Fig. 14). Rims are made of cast metal, either iron or steel, of laminated or rolled plates, or of combinations of both. The allowable peripheral velocity of cast iron is about 5000 ft., of steel-casting 8000–10 000 ft., and laminated rims may have velocities of from 14 000 to 18 000 ft. per minute.

Where cast-iron rims are used the poles are sometimes countersunk to give additional contact-area. As a rule, solid rims are made of steel and may be in one piece with the arms and hub or may be separate and the spider be of iron. In the latter case, the rim may be shrunk on the arms or bolted to it. When shrunk on, one or more keys are placed on the periphery for driving. The rims are occasionally made of standard fly-wheel construction with one arm and the corresponding portion of rim to a section, the whole held together by links. Making the arms separate from the rim, removes the shrinkage strains, and allows the use of a cheaper metal—cast iron for the arms and hub—while requiring more machine work. Alternators with bad regulation will often run for a considerable time on short-circuit without harm, so that the resultant shocks from such causes are less than with direct-current generators. When the field and fly-wheel are combined, both the driving and the retarding forces are located in the fly-wheel rim and the only stresses in the arms and shaft are such as come from the prime mover.

As a general rule and within limits, the higher the speed the lighter in weight will be both the prime mover and the generator. Commercial considerations in some instances and the height of waterfalls and water-wheel design in others, demand a high rotative speed and a high peripheral velocity for units of large output. Now alternators are always designed with regard to limits which are different for different conditions. For units of high speed and large output these are the mechanical stresses in the revolving part. In most cases, these must have a considerable factor of safety at 50% above normal speed; a condition which may easily exist. It is then necessary to work with materials the properties of which are accurately known and which has the greatest possible strength. For these reasons, the best practice is to make rims of built-up rolled-steel plates riveted

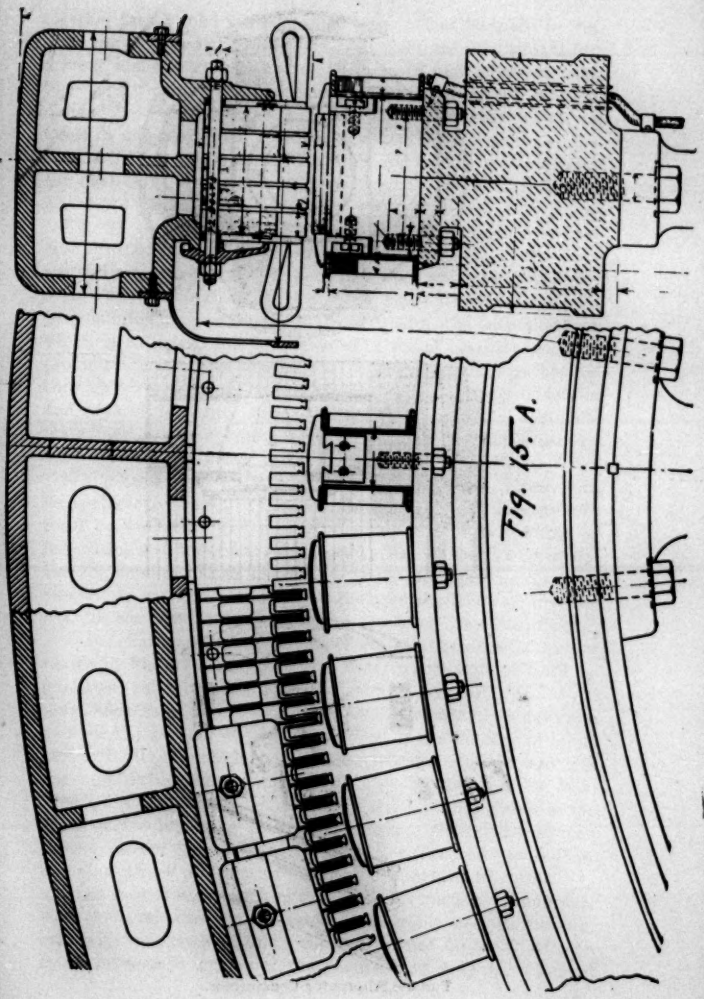


Fig. 15.A.

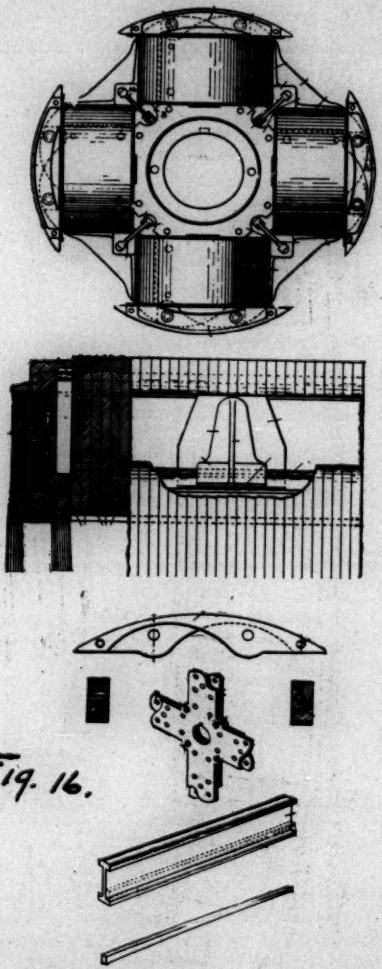


Fig. 16.

Turbine Alternator Constructor.

together into a solid self-contained ring. The dovetails in the arms may be straight, in which case they are used simply for driving, and the only tension on the arms is such as comes from their own weight. In other cases, the resisting stresses may be divided between the arms and the rim. The poles are either made in one piece with the rim laminations, in which case the shoe, if there is one, is made removable and retains only itself and the field coils, or the pole may be held by any of the various methods shown.

Fig. 15 illustrates the construction of a modern fly-wheel alternator of the " engine-type "; the hub is split and the arms are hollow; two different rim-constructions are shown; the rim is built up of laminated iron, in one case held to the inner cast iron by small dovetails with nearly straight sides, the only object of which is to drive, and in the other a radial cast-iron section, projects through the laminations, which are held together by through rivets in both cases. The poles are held by dovetails and keys on the outer surface of the fly-wheel rim. The laminated places lap in alternate layers, giving a rigid construction. A cast-steel construction is illustrated in Fig. 15*a*.

While high-speed water-wheel and turbine-driven alternators do not have fly-wheels in the ordinary sense, the rim-construction must be unusually strong, and for this purpose a number of interesting solutions have been found. Fig. 16 shows a construction for small machines where it is possible to make the rim from one sheet, and the projecting pole-shoes are made removable. Fig. 16*a* shows a modification of the preceding assembled field.

A peculiar tangential, bicycle-spoke construction is clearly shown in Fig. 17. A high-speed water-wheel type of built-up laminated rim with plate supports is illustrated in Fig. 18.

In many cases two rows of arms are preferable; it is desirable to have the number of poles a multiple of the number of arms, although this cannot always be done; in engine-driven machines the number of poles should if possible be divisible by four. Where a separate fly-wheel is used, it is sometimes bolted to the arms of the revolving part to relieve the shaft from sudden shocks; arms are elliptical in section, either solid or hollow. Sometimes they are cast into various channel- and I-forms.

Hubs do not vary much in design; conveniences of manufacture or transportation may make it desirable to part the hub, otherwise it is made in one piece and pressed on the shaft. In small high-speed machines the laminations may be mounted

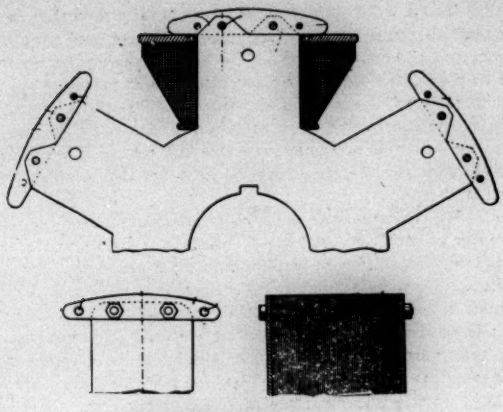


Fig. 16A.

High-Speed Revolving-Field Construction.

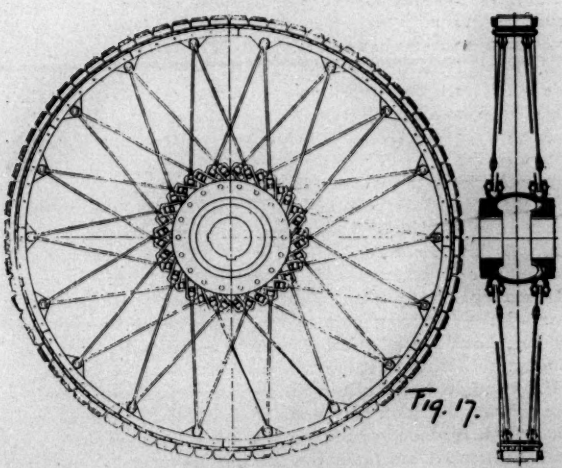


Fig. 17.

Bicycle-Spoke Construction.

directly on the shaft, in which case it is desirable to use at least two keys.

Field-Coils.

Field-coils are wound with either wire or copper strip; the number of poles and necessary exciter pressure sometimes prohibit the use of strip winding, but wherever possible it is now used. The art of bending thin copper strip is one of recent development; coils wound in this manner have radiation constants several times greater than wire-wound coils. The outer surface of the coil is exposed to the air and thin sheets of paper separate adjacent strips. by baking the coils under pressure, the separate layers may be cemented into a solid mass. Wooden or fibre washers are placed at top and bottom of coil and insulation between the winding and the pole core; the terminals are riveted and soldered to the strip and are made of a material that does not crystallize by vibration. Strip-winding is much easier to retain in place at high speeds, but still requires additional retainers under abnormal conditions. The centrifugal force acts in a radial direction and with few poles may cause a bulging of the winding unless prevented by such devices as are shown in Fig. 19, which illustrates field-coil sections and methods of insulation in use at present.

The ends of the coils may be either round or straight. With high-speed machines, it is necessary to relieve the pole as much as possible from supporting the coil, and straps are commonly placed over the ends and fastened, independently of the pole, to the revolving rim. With slow-speed machines, a cast-metal retainer projecting over the exposed portion of the pole is fastened to the pole-end. Brass rings are occasionally placed around the poles to prevent injury from accidental field opening.

Poles, Pole-Shoes, and Methods of Fastening.

The various poles, pole-shoes, and methods of fastening the same are shown in Fig. 20, which illustrates most of the modern forms. Poles may be either of solid section, steel casting or wrought iron, or may be built up of laminations of rolled plate.

Laminated poles are of known strength and section built up into an even form, require no machine work, may be made in one piece with laminated rim, and necessitate a rectangular pole-section. They allow the use of wide slot openings and small mechanical clearances, the easy introduction of pole-face windings, the sudden variation of magnetic flux. With them the effective cross-section is reduced from 5 to 10%, depending on

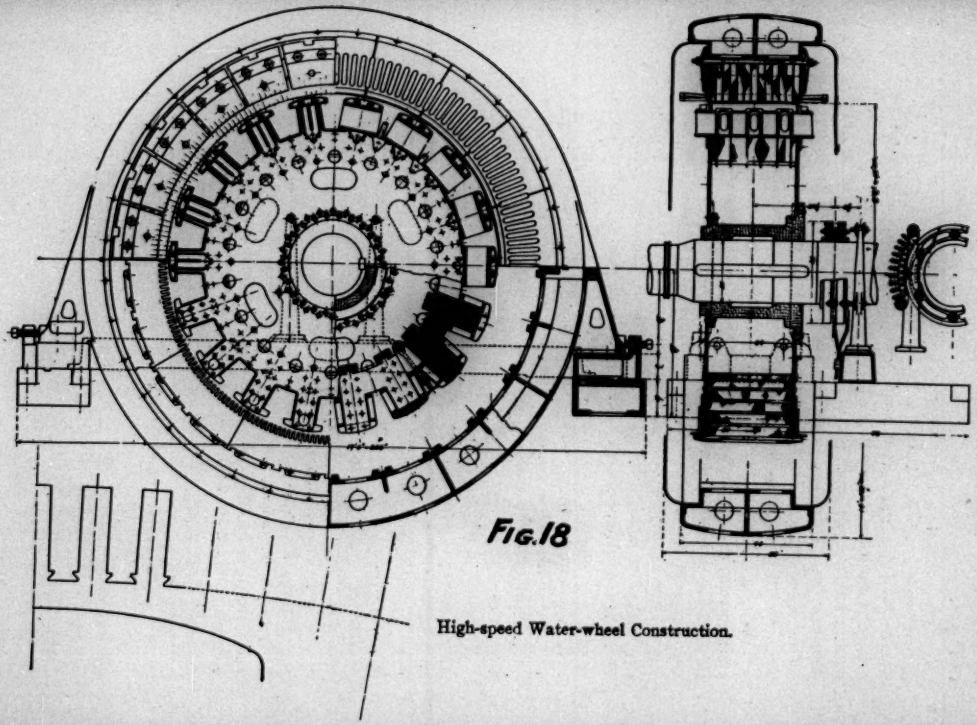


Fig. 18

High-speed Water-wheel Construction.

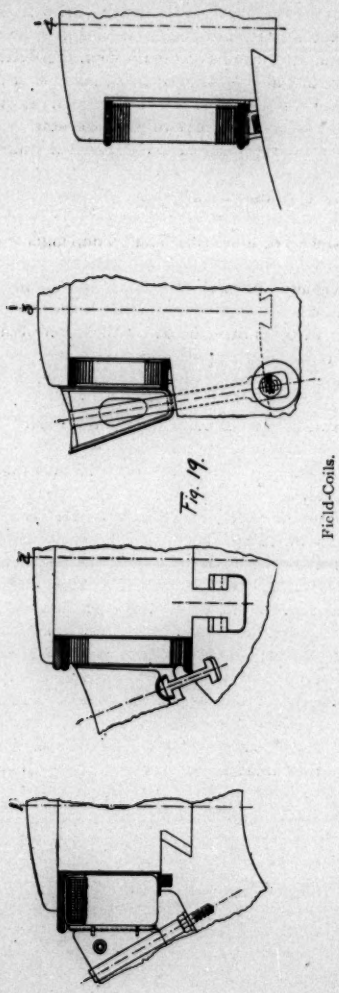


Fig. 19.

Field-Coils.

the thickness of the plate used, which varies from 0.0125 to 0.125 in., the thicker plates being used for large mechanical stresses. Laminated iron has more uniform properties than cast metal and may be safely worked at higher magnetic densities.

Cast poles are almost universally of steel. They are likely to contain sand or blow-holes, require machine work for mounting, unless, as in very exceptional cases, cast on the rim. The sides may be irregular and require machining or wedges for fitting field coils. Cast poles may be made of any desired section, suffer no reduction in effective cross-section and are easily held by bolts. If the tip or shoe is also solid, small gaps require closed or partially-closed slots but offer a resistance to hunting. With very high peripheral velocities separate cast poles become impossible due to the necessary size of bolts to retain them.

The number of poles being fixed by the speed and frequency by the relation

$$\frac{\text{No. Poles} \times \text{rev. per. min.}}{120} = \text{frequency, in cycles per second.}$$

The peripheral velocity is consequently dependent on the pole-pitch.

Peripheral velocity (ft. per min.) = 10 × pole-pitch (in.) × cycles per second.

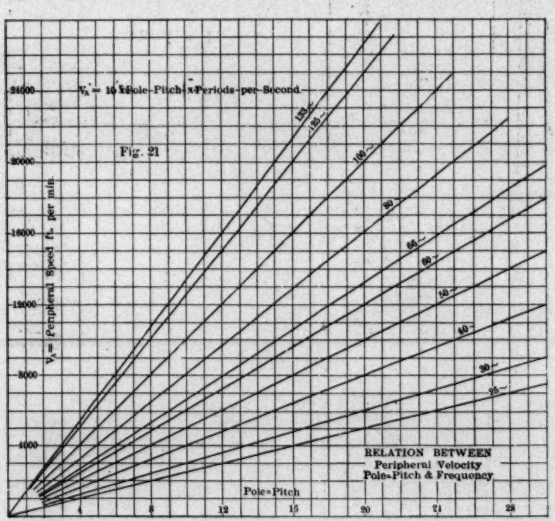
The accompanying sheet, Fig. 21, shows clearly the relations and limitations in this respect. A minimum pole-arc being practically fixed by the desired winding distribution, the necessary gap is determined for mechanical reasons and economical magnetic densities. It is seen that the limiting peripheral velocity is more quickly reached as the frequency increases. If the peripheral velocity is kept constant, it is not always possible to save in material by increasing the speed. The natural relations which determine the peripheral velocity may be seen in part from the following:

The slot-depth is fixedby electrical reasons, and for a given line of machines approximates more or less closely to a constant value. The slot-width and its relation to the slot-depth are variables, only within limits, as well as the relation between the widths of tooth and slot. The current-density and space-factors being determined by other reasons of heating and dielectric strength, there results a value for width of tooth and slot and for the amperes per inch of circumference, a nearly constant quantity for a given type of machine. The number of slots per pole for two- or three-phase must be divisible by the number of phases,

Fig. 20.

Poles, Pole-Shoes and Methods of Fastening.

and when the same punchings are to be used for either, must be divisible by six. It therefore happens that most alternators are built with 6 or 12 slots per pole, 12 slots being used where the kilowatts output per pole is high and it is not desirable to increase the length to the amount necessary for six slots. Nearly all engine-driven alternators have six slots per pole, which gives a pole pitch of about 10 in., and a peripheral velocity which varies directly with the frequency. The peripheral velocity in ft. per min. might very roughly be taken as 100 × frequency. This is



however, subject to wide modifications and machines of low frequencies usually run at much higher velocities than this would give. The peripheral velocity may vary as the square root of the frequency. The relations between peripheral velocity, pole-pitch and frequency are shown in Fig. 21.

Round poles may be used under certain conditions and allow of saving in field copper and give good ventilation. Rectangular poles which depart far from square do not best utilize active materia!.

The desired relation between magnetic densities in the pole-core and at the pole-face necessitates that the pole-shoe extend beyond the core around the circumference. This also serves to hold the field coil in place. The length of the pole-arc varies from 50 to 70% of the pole-pitch; the relation being a compromise between opposing tendencies. In one type of alternator the tip is not extended; the coil is held in place by a wedge extending between poles; in this machine the magnetic relations are necessarily of different values.

Pole-tips or shoes may be in one piece with the pole or separate; the shoe may be laminated while the pole is either laminated or

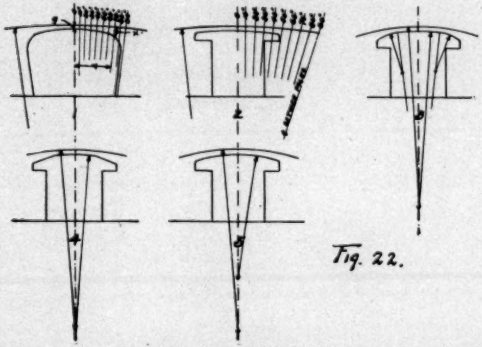


Fig. 22.

Forms of Pole Shoes.

solid. It is necessary to have the field-coil easily removable and in some cases to be able to remove the poles in order to gain access to the armature coils where there is no arrangement for sliding the yoke along the base. No. 6, 8, 9, and 14 show methods of attaching laminated tips to solid poles.

Pole 1 is of representative form for laminated section, although it might be used for solid. The method of holding the pole is of interest. The dovetail is cut diagonally in the rim which is usually of solid-steel section. The dovetail projection on the pole is straight, *i.e.*, parallel to shaft. There is a key on each side of the pole. One side of the key—that against the pole—is straight, while the other side is inclined to fit the groove in the rim. The shoulders of the pole rest on the rim while a slight clearance exists

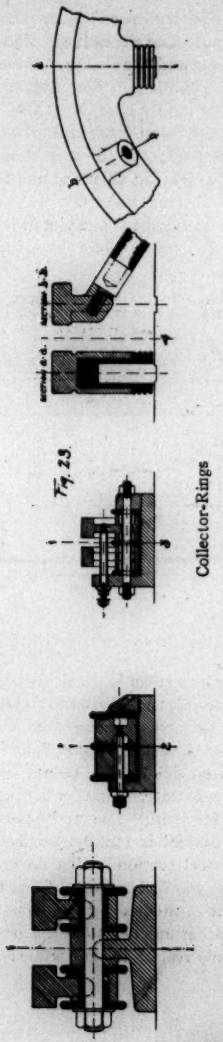


Fig. 23.

Collector-Rings

at bottom. The heating of the pole will tighten the joint, the keys allow the pole to be accurately centered and by the insertion of shims under the shoulders, the clearance may be changed slightly. Poles are interchangeable and with end-plates against keys cannot become loose during operation. The laminations are held in place by bolts or rivets and are assembled as solid pieces. The dovetails are cut in the rim by first cutting out the rectangle with a slotter and then the angles with an end-milling cutter.

Pole No. 2 is a modification of No. 1. The dovetail is cut straight and the two taper keys are on the same side of the pole.

Pole No. 3 is the same general plan. Instead of using keys the pole is slotted at the bottom and after being placed in the dovetail, a round key with inclined parts is driven in the central hole spreading the iron sufficiently to insure a tight fit. There may be two or more slots.

Pole No. 4. Shows two methods of holding pole which are self-explanatory.

Fig. 5 shows a method of bolting laminated poles to yoke. A square or round bar runs lengthwise of the pole through the laminations into which the bolts are tapped. The contact-area and section are slightly diminished. The pole may easily be saturated. An alternative method is to sink the bolt-head into the laminations instead of the bar. This method of holding the pole is well adapted for use on engine-type generators. It allows of easy assembling and removal, and in practice is found not to become loose.

Fig. 6 is a solid pole with laminated tip dovetailed and the whole bolted to the yoke.

Fig. 7 is a solid pole bolted through from top.

Fig. 8 is a curious and apparently expensive foreign construction. In this case the pole is round and is fixed in position by a dowel-pin.

Fig. 9 is of interest as showing a unique method of holding pole-tips.

Fig. 10 shows a method of retaining poles used by the Allegemeine Elektricitats Gesellschaft for machines with high peripheral velocities.

Fig. 11 shows a method for retaining poles where the rim consists of laminated iron as well as the poles, and where the extended pole-tip is in one piece with the pole-core. The laminations in the rim are built up in short sections of from one to two

inches, which are riveted and the whole held together by through bolts. The pole laminations are alternated as shown to match the similar sections of the core and the whole is held by taper keys as shown.

Fig. 12 shows a design for the same purpose as the preceding. The pole is built up solid from laminated iron and inserted endwise into the rim. It is there drawn tight against the rim by taper keys. This is used on high-speed machines of large output and has proved a very satisfactory method where the mechanical stresses are great.

Fig. 13 shows a foreign method of countersinking a round pole into the rim, and the use of a dowel-pin to prevent turning. With a cast-iron rim this construction is good, but also expensive. The added security against tilting of the pole is not great.

Fig. 14 shows an unusual construction, sometimes used in small machines, of casting the pole in one piece with the rim. The shoe which may be solid or laminated, is screwed on from the top. Should the poles come unevenly spaced on the casting it is difficult to compensate therefore by a small shifting of the shoe.

Figs. 15, 16, 17, 18, and 31 illustrate different methods of holding the poles on inductor alternators.

Fig. 15 illustrates present practice in this country. Fig. 31 illustrates a cheap method of holding by babbitt which can only be used where the centrifugal force is small.

Fig. 19 is the same method as in Fig. 12, except that the keys force the pole up instead of drawing it down. It does not appear to have any compensating advantage.

Fig. 20 shows a method which is often cheaper than the dovetail construction.

Fig. 21 shows a foreign construction. The windings placed directly on the poles which are then mounted adjacent to each other and supported entirely by the through bolts as shown.

Fig. 22 illustrates a construction used in this country where the pole-tip is not extended and where the yoke-ring is laminated and made in one piece with the poles. The rim may be used for a fly-wheel or not as conditions prescribe. The field-coil is retained by a wedge between adjacent poles.

Fig. 23 is a very interesting construction used for high-speed machines. The lamination embraces two poles and extends on one side to the air-gap and on the other to the bottom of the pole-tip. The plate used is 0.125 in. thick and a number of similar plates are built up together. As the plates cover two poles but

one-half of the rim-section between is iron, and by building up three plates of each kind before reversing we have numerous ventilating ducts alternating with the iron section extending across the core and affording excellent ventilation. Numerous bolts pass through the laminations, making the whole self-contained and independent of the dovetail supports which are used merely for construction and alignment. The pole-tips are separate and are inserted between the projecting laminations after the coils have been put in place. Rods are then run through, securely fastening the tips in place. In this manner the central part of the pole face is continuous, while the edges where the tips project, are broken.

Fig. 24 is similar to 22 except that the pole-tips project and the poles are wound by hand with flexible cable after the field-iron is assembled.

Fig. 25 is a construction used for small high-speed machines such as are suited to turbine work. The pole and central part are made in one piece and are riveted in sections the whole being held together by long bolts or rivets. The pole ends in a double-curved surface which is reversed every alternate section. Two adjacent sections of the pole-shoe are riveted together and are then inserted into the corresponding places in the pole-end. Long rods running through both hold the shoe in place.

Fig. 26 is a variation of the same method.

Fig. 27 is a method of retaining the poles by double row of bolts, and Fig. 28 of simply tapping directly into the laminations.

Fig. 29 shows each pole with a separate base which latter is bolted to the rim and Fig. 30 another method of bolting and a detachable pole-shoe.

Form of Pole-Shoes.

The distribution of the magnetic flux on different parts of the pole-face, is largely determined by the length of gap at any point to which the magnetic density is almost inversely proportional. If we have one slot per pole per phase, the wave of electromotive force practically coincides with that of field distribution. With more than one slot per pole per phase, the tendency is for the wave of e.m.f. to approximate a sine form independent of the law of distribution of the magnetic flux. If with open slots the strength of the field be not graded near the pole-edge, harmonics are introduced into the wave form. There are several methods of shaping the pole-face in order to get the desired sine wave with a sufficient degree of approximation. (Shown in Fig. 22.)

No. 1 shows the pole on a S.K.C. inductor alternator. Here the gap is so laid out as to give a theoretically perfect sine wave. The distance between the centers of two consecutive poles in this type of machine represents 360° electrical. Starting from the centre of the pole with a gap equal to g, we have for the gap g^1, at any point x at an angular distance from the centre line equal to α electrical degrees. $g^1 = \frac{g}{\cos \alpha}$

Fig. 2 is for a machine the adjacent poles of which are of opposite polarity. Here the distance between pole centres represents 180° electrical, and the pole-face is laid off as before with this difference.

Figs. 3, 4, and 5 show methods of approximation which may give results which agree quite closely with those obtained from a theoretical curve. Fig. 3 is a compound curve. Fig. 4 has the central part of the pole-arc drawn from the centre of the armature. The edges of the poles have straight bevels. In Fig. 5 the pole-arc is drawn with a radius less than that from the armature centre to gap. With proper judgment any of these methods will be found to give satisfactory results.

Collector Rings.

A great disadvantage in the revolving-armature type of alternator is the difficulty of taking high-pressure current from the machine. The continuity of insulation must be broken and the exposed brushes and collector are always possible sources of danger. While with the inductor alternator we have no moving wire and consequently no moving contacts, with the revolving-field generator the low pressure exciting current must be led into the field-coils by means of collector rings. The forms in common use are shown in Fig. 23. The rings are usually made of cast iron, and carbon brushes are employed. Several brushes per ring are used to allow for repairs or adjustment without interruption of service. The collector is preferably made open, especially if much heat is generated. Different methods of supporting and insulating the rings are shown.

A paper presented at the 186th Meeting of the American Institute of Electrical Engineers. New York, April 22nd, 1904.
Copyright 1904, by A. I. E. E.

A CONTRIBUTION TO THE THEORY OF THE REGULATION OF ALTERNATORS.

BY H. M. HOBART AND F. PUNGA.

The interesting paper recently contributed by Behrend to the proceedings of the INSTITUTE has incited the writers to the preparation of the present paper, which sets forth their own views regarding the regulation of alternating-current generators.

It is unnecessary to refer to the theories of others, since these have so recently been discussed by Behrend*, who has shown by means of practical examples that none of these theories give correct results for different types of machines.

The theory which the writers describe in this paper has been tested on but a limited number of machines, but has in these cases given such excellent results as amply to justify its publication, in the hope that this will lead to its being subjected to further tests in impartial quarters. Moreover, the writers entertain the hope that the theory itself will, independently of practical examples, prove convincing in virtue of its freedom from hypothetical assumptions. Nevertheless its reliability must of course be demonstrated by testing it by a large number of practical examples of various types of machines. It is our intention to bring together such practical examples in a treatise on the design of alternating-current generators, in which this theory will be employed in the sections relating to pressure regulation.

The change in the pressure of a constantly-excited alternating-current generator when its load is varied in nature or amount, is

*TRANS. Am. Inst. Elec. Eng'rs., Vol. XXI., p. 497.

chiefly occasioned by the magnetic flux set up by the current in the armature winding and linked with the turns constituting the winding. These lines may be classified according as they flow in one or the other of three paths, as shown in Fig. 1.

First Path—The lines never emerge from the armature. They consist of those which cross the armature slot from side to side, and those which are linked with the end connections.

Second Path—The lines emerge from the armature and cross the air-gap toward one end of the pole-shoe, and after passing along the pole-shoe, return across the air-gap to the armature from the other end of the pole-shoe.

Third Path—The lines, after emerging from the armature,

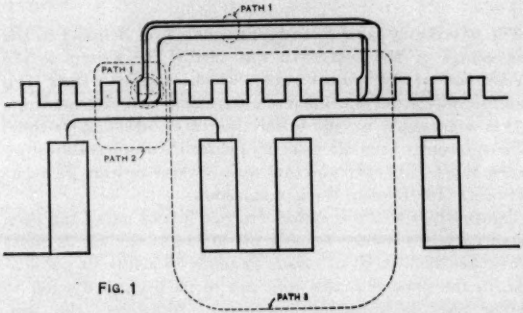


FIG. 1

traverse successively the air-gap, pole-shoe, magnet-core, yoke, adjacent magnet-core, and pole-shoe, and after again traversing the air-gap, re-enter the armature.

The lines following the *first path* are purely self-inductive, and all methods of treatment in which they are correctly handled are applicable also to our theory.

Hence for sine curves of electromotive force and current, one applies the recognized vector diagram of Fig. 2 in which

OA = The electromotive force generated in the armature winding by the lines crossing the air-gap = internal e.m.f.

OC = Current flowing in the windings.

$OD = BE$ = The reactance-pressure generated in the armature winding by the current OC flowing in it.

AB = Pressure-drop due to ohmic resistance.

OE = Terminal pressure.

α = Angle $A\,O\,E$ between internal e.m.f., $O\,A$, and terminal e.m.f $O\,E$.

ϕ = Angle $E\,O\,C$ between terminal e.m.f $O\,E$ and current $O\,C$.

The magnetic flux belonging to the second and third paths, can be best considered if we, for the moment, neglect the magnetic reluctance of the iron (armature laminations, magnet core, and yoke).

In Fig. 3 is shown a magnet-pole with a single armature conductor at the centre of the polar pitch. When the conductor carries no current, the magnetic flux across the air-gap will

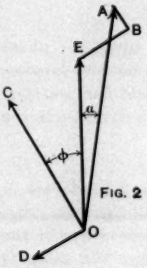


FIG. 2

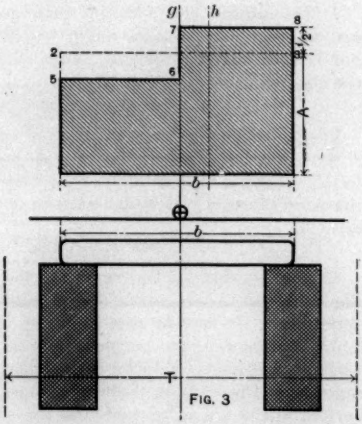


FIG. 3

be generated solely by the field magnet ampere-turns, and will be uniformly distributed over the pole-arc. It may be represented by the rectangular area 1 2 3 4, the spreading at the pole-tips being neglected.

Let us now consider the case when a current of i amperes flows through the conductor; the ampere-turns per field-spool will be denoted by A; the total armature strength per pole, denoted by $i/2$, is, according to the conditions of load, to be added or subtracted from the field ampere-turns A.

In the case shown in Fig. 3, the left half of the pole-arc is subject to the influence of $(A - i/2)$ ampere-turns; the right half, to $(A + i/2)$ ampere-turns. The density of the magnetic flux is pro-

portional to these ampere-turns, since the magnetic reluctance of the iron is, for the time, neglected. The distribution of the magnetic flux may now be diagrammatically represented by the area 1 5 6 7 8 4 shown in Fig. 3. What now, is the effect of this distribution?

In the case under consideration, where the conductor lies at the middle of the pole-pitch, the total number of lines of force entering the armature is unaffected by the armature current; *i.e.*, the area 1 5 6 7 8 4 is equal to the area 1 2 3 4 and what has been lost on the one side of the conductor has been exactly made up by the gain on the other side.

2. The internal electromotive force generated by this flux is not only not decreased, as might hastily have been concluded, but is even slightly increased, as is evident when we consider the electromotive force formula

$$E = k\,T\,N\,M \times 10^{-8}$$

The periodicity N, the total flux M, and the turns per phase T have not been altered, but k has become slightly greater, for the alteration in the form of the magnetic field has precisely the same effect on k as would occur in virtue of a decrease in the ratio of

pole-arc : pitch.*

3. Another effect of the current in the armature conductor in Fig. 3, relates to the shifting of the central line of the total magnetic flux.† It may be seen from Fig. 3 that the centre of the figure representing the magnetic flux is no longer the same as when the armature-conductor carried no current. The line g then represented the centre of the flux; the magnetomotive force of the current in the armature-conductor has shifted the centre of the resultant flux distribution to the line h. These considerations are capable of being readily extended to the case of the flux distribution where the conductor occupies any other than the middle position opposite the pole-arc. The flux distribution in such a case is illustrated diagrammatically in Fig. 4, and the principal difference between this flux distribution and that of the previous case where the conductor occupied the middle position is seen to consist in a decrease in the

*The dependence of k upon the ratio of pole-arc to pitch was probably first pointed out by Kapp. It is very exhaustively treated on pages 82 to 85 of "Electric Generators."

†First pointed out by Blondel (*L'Industrie Electrique*, 1899).

total number of magnetic lines due to the current in the conductor, whereas in the former case the total number of magnetic lines remained unchanged.

Of the three considerations enumerated above, we shall confine our attention to the first and third; since the influence of the change in k is comparatively slight, and since also it is, in actual practice, largely or altog her offset by the increasing magnetic reluctance of the teeth, consequent upon the increased local saturation brought about by distortion. Hence it is not only simpler, but actually more correct to disregard both of these opposing influences.

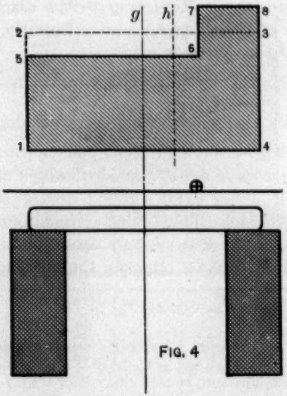


FIG. 4

In order to study more carefully the influence of the armature magnetomotive force upon the magnitude and distribution of the magnetic flux, the diagram of flux distribution in Fig. 4 has been reproduced in Fig. 5. Since our purpose is to compare the flux distribution in the same machine under two different conditions we do not need to employ absolute values, but may represent by A the ordinate of the plane rectangular figure representing the flux distribution when there is no current in the armature-conductor, setting its abscissa, the pole-breadth, equal to b. The abscissa representing the position of the conductor measured from the right-hand end of the pole-face, may be designated by x. From the figure we obtain at once:

Number of magnetic lines entering armature when there is no current in the conductor $= A\,b$

Number of magnetic lines entering armature when the conductor carries the current $i = A\,b - (i/2\,b + x\,i)$.

The calculation of the amount of shifting of the centre of the total magnetic flux consists in ascertaining the position of the ordinate passing through the centre of gravity of the surface. When no current flows, it is obvious that the magnetic and geometric centres are identical. But this identity must also occur in the extreme case represented in Fig. 6, where the armature magnetomotive force, $i/2$, equals that of the field-magnet spool. The magnetic and geometric centres are also identical in all intermediate cases. Returning to the diagram of Fig. 5, let the distance of the magnetic centre from the mid-pole position be designated by y; then:

$$y = \tfrac{1}{2}\,\frac{x\,(b-x)\,i}{A\,b - (b\,i/2) + x\,i} \quad *$$

Conductors lying between adjacent pole-tips are without influence upon the factors $x\,(b-x)\,i$ and $x\,i$, which are proportional to the distortion. They exert a direct demagnetising influence and thus affect the total flux. Hence, in obtaining the values of the factors $x\,(b-x)\,i$ and $x\,i$, only those conductors are to be considered which lie directly opposite the pole face. But in ob-

*This formula is derived as follows (Fig. 5):

$$\text{Total surface} \times y = \text{surface } (1\,2\,3\,4) \times \left(-\frac{b}{2}\right) + \text{surface } (3\,6\,7\,4) \times (+b/2) + \text{surface } (5\,8\,9\,6) \times (b/2 - x/2)$$

Since surface (1 2 3 4) = surface (3 6 7 4), we have

$$y = \frac{\text{Surface } (5\,8\,9\,6)}{\text{Total surface}} \left(\frac{b}{2} - \frac{x}{2}\right)$$

$$\text{The ratio } \frac{\text{Surface } (5\,8\,9\,6),}{\text{Total surface}} \text{ is, however,}$$

equal to

$$\frac{x\,i}{A\,b - (b\,i/2) + x\,i}$$

hence, in general

$$y = \tfrac{1}{2}\,\frac{x\,(b-x)\,i}{A\,b - (b\,i/2) + x\,i}$$

taining the value of $(b\,i/2)$, the total number of conductors per pole should be considered.

The calculation of the pressure-drop in a machine would by this method be far too laborious. But fortunately the method may be greatly simplified for the case of sine curves of electromotive force and current.*

Sine-Wave Alternators.

In the many cases where we may for practical purposes assume a sine-wave form of electromotive force and current, the decrease in total magnetic flux as the result of the armature interference, may be attributed to and derived from the demagnetizing

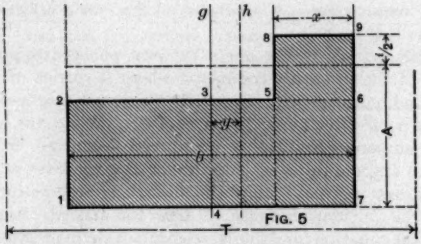


Fig. 5

ampere-turns, and the shifting of the flux centre, to the distorting ampere-turns.

The magnitudes of these values, as dependent upon the ratio pole arc: pitch are given in Table I.† for a single-phase alternator

*Since it is sometimes required to calculate the pressure-drop for machines where sine-wave assumptions are not permissible, this general analytical method is followed out to its conclusion in the Appendix, and therein are also set forth the uninteresting but essential steps leading up to the derivation of Table I. which result alone amongst the matter contained in the Appendix is essential to the application of the theory to those alternators in which a sine-wave assumption is justifiable. For practical purposes this is generally found to be the case, hence the contents of the Appendix possess interest only for those who wish to follow through the steps leading up to the practical results. Those who only wish to satisfy themselves of the soundness of the method, can do so by applying it to machines with which they are familiar, in the way illustrated in this paper.

†The derivation of Table I. is given in Appendix, as indicated in the preceding footnote.

with one slot per pole, when loaded to an armature strength of $n\,i$ effective armature ampere-turns per pole.

TABLE I.

DEMAGNETIZING AND DISTORTING AMPERE-TURNS FOR THE CASE OF A UNI-SLOT, SINGLE-PHASE ALTERNATOR.

	$b/\tau = 0.5$	$b/\tau = 0.6$	$b/\tau = 0.7$
Demagnetizing ampere-turns	$0.82(n\,i)\sin\phi'$	$0.78(n\,i)\sin\phi'$	$0.75(n\,i)\sin\phi'$
Distorting ampere-turns	$0.11(n\,i)\cos\phi'$	$0.15(n\,i)\cos\phi'$	$0.20(n\,i)\cos\phi'$

In Table I.: ϕ' is the angle between pole-centre and that position of the armature-conductor where it carries maximum current and, consequently, exerts its maximum magnetomotive force, the polar-pitch being taken as 180°. While the demagnetizing ampere-turns are to be directly deducted from the field-spool ampere-turns in determining the resultant magnetomotive force, we may, from the distorting ampere-turns, determine the angular distance, β, from the magnetic centre by means of the equation for β the degrees shift of the magnetic centre;

$$\beta = \frac{\text{Distorting ampere-turns per pole}}{\text{Air-gap ampere-turns per pole}} \times 90°*$$

The influence of the pole-arc on the demagnetizing and distorting ampere-turns is of considerable interest. With increasing ratios of

Pole-arc : pitch

the demagnetizing ampere-turns very slowly decrease. But the distorting ampere-turns, on the other hand, increase, and very rapidly; in fact their rate of increase is as the square of the increase in the ratio of pole-arc to pitch. This circumstance may be of importance in the choice of the pole-arc. When, for instance, a certain closeness of regulation for $\cos\phi = 1$, is required, it may be distinctly advantageous to design the machine with a relatively small pole-arc and thus decrease the distor-

*It might be more exact in some cases to make some allowance for the magnetomotive force required by the teeth.

tion. But when it is required to obtain a given degree of regulation for $\cos \phi = 0$, one will obtain the best results by means of a larger pole-arc.

Single-Phase Distributed Windings.

It is relatively simple to extend the calculations to other types of winding. Thus, when the single-phase alternator has many slots per pole, or a uniformly distributed winding, both the demagnetizing and distorting influence will be somewhat less; since for the different sections of the winding the maximum magnetomotive force occurs when these sections occupy different positions with respect to the pole-centre. When, for example, one side of a winding covers one-third of the pole-pitch, it will be necessary to multiply the values given in Table I. for the armature interference, by 0.95. This quantity is designated the "breadth-factor" and has, for various types of winding, the values set forth in Table II.

TABLE II.

Percentage of polar pitch covered by one side of the armature winding.	"Breadth Factor"
20%	0.99
40%	0.94
60%	0.86
80%	0.76
100%	0.64

Application to Polyphase Generators.

Nothing new is encountered in applying these principles to the case of polyphase generators. One must merely first calculate the armature interference for one phase and then multiply the values thus obtained by the number of phases. The ampere-turns are thus combined algebraically and not geometrically.* The correctness of this proposition is at once recognized when it is considered that all the phases are identical; for we have the same number of turns, and the same current

*An experimental proof for this assertion may be found in Table IV, page 197, which shows the agreement between observed and calculated values for 7 single-phase generators and for 11 three-phase generators.

per turn, and the current reaches its maximum value for all phases when at the same distance from the mid pole-face position.

In order to make the final forms of the expressions for the demagnetizing and distorting ampere-turns as simple as possible, we shall denote the effective ampere-turns per armature pole by $n\,i$, and combine the results of Tables I. and II. in Table III.

TABLE III.

GENERAL CASE FOR DEMAGNETIZING AND DISTORTING AMPERE-TURNS.

	Armature Ampere-turns (effective) per pole.		
	$b/\tau = 0.5$	$b/\tau = 0.6$	$b/\tau = 0.7$
Demagnetizing ampere-turns	$0.82\,B\,n\,i \sin \phi'$	$0.78\,B\,n\,i \sin \phi'$	$0.75\,B\,n\,i \sin \phi'$
Distorting ampere-turns	$0.11\,B\,n\,i \cos \phi'$	$0.15\,B\,n\,i \cos \phi'$	$0.20\,B\,n\,i \cos \phi'$

The application of these principles to the results obtained experimentally on a typical alternator will suffice to show the method of applying this theory of the regulation of alternators. The machine investigated was one of the three-phase generators installed at the Shepherd's Bush Power-House of the Central London Railway. The rated output is 850 kw. at unity power-factor. The machine has 32 poles, and a speed of 94 rev. per min., the periodicity being 25 cycles per second. The pressure between terminals is 5000 volts, corresponding to 2880 volts per phase, and for each of the Y-connected armature windings.

The leading dimensions are set forth in the following specification:

ARMATURE.

Internal diameter	3666	mm.
Gross width of armature core between flanges	368	"
Number of ventilating ducts	5	
Width of each ventilating duct	13	mm.
Effective width of armature core	274	"
Number of slots	192	
Number of slots per pole per phase	2	
Depth of slot	92	mm.
Width of slot	33.4	mm.

FIELD.

Length of pole-arc	228	mm.
Polar pitch	360	mm.
Ratio of pole-arc to pitch	63.3%	
Radial length of magnet-cores	840	mm.
Diameter of field	3650	mm.
Radial depth of air-gap	8	"
Dimensions of cross-section of magnet-core	16.5×37	sq. cm

WINDING.

Number of armature conductors	2688	
Number per slot	14	
Number of turns per pole and per phase	14	
Effective armature ampere-turns per pole and per phase at full-load current of 98 amperes	1380	
Each armature conductor consists of 26 strands of No. 17 B. W. gauge.		
Mean length of one armature turn	161	cm.
Embedded length	55	"
Free length	106	"

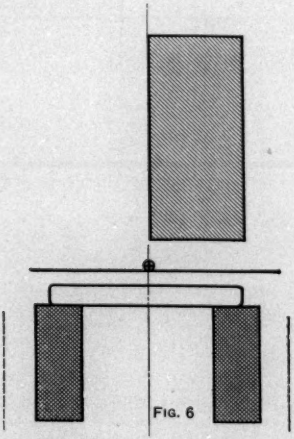


FIG. 6

We shall first calculate the short-circuit current, since this is generally experimentally observed, and constitutes a good test of the theory. The estimation of the short-circuit current requires a determination of the inductance of the winding. With straight-sided slots a good approximation to the inductance

of the embedded part may be obtained by elementary magnetomotive force calculation thus:

Let D = depth of slot in centimetres.
d = depth above top of winding in centimetres.
W = width of slot in centimetres.

The number of lines per ampere-turn per centimetre of embedded length, may, for the case of the inductance of the winding of a single slot, be taken as approximately equal to

$$\frac{4\pi}{10}\,\frac{\frac{1}{2}(D-d)+d}{W} = 0.63\,\frac{D+d}{W}\ \dagger$$

In the case in question (see Fig. 7)

$D = 9.2$ $d = 1.2$ $W = 3.3$

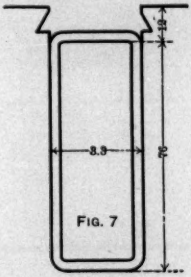


FIG. 7

$$\text{Number of lines} = 0.63 \times \frac{9.2+1.2}{3.3}$$

$= 1.99$ per centimetre of embedded length and per ampere-turn. Now, there are two slots per pole per phase, hence the length of the magnetic path through air is doubled and the number of lines per ampere-turn per centimetre of embedded length becomes $1.99/2 = 1.00$.

It has been demonstrated* that the number of lines per ampere-turn per centimetre of free length may be taken at from 0.4 to

*" Modern Commutating Dynamo Machines, with Special Reference to the Commutating Limits," by H. M. Hobart, *Proc. Inst. Elec. Engrs.*, Vol. 31, p. 170.

†Those components of the magnetic dispersion associated with air-gap and ventilating ducts, which in practice it is troublesome to calculate, are taken into account by increasing the theoretical value $\frac{1}{3}(D-d)$ to $\frac{1}{3}(D-d)$.

0.8. As a rough approximation we may estimate them as follows:

0.8 lines for 1 slot per pole and per phase
0.7 " " 2 " " " " "
0.6 " " 3 " " " " "

Thus in the case under consideration we obtain: $55 \times 1.00 + 106 \times 0.7 = 55 + 74 = 129$ lines per ampere-turn†.

The inductance per spool of 28 turns is

$$28^2 \times 129 \times 10^{-8} = 0.00100 \text{ henrys}$$

and the reactance is

$$2\pi \times 25 \times 0.00100 = 0.157 \text{ ohms}$$

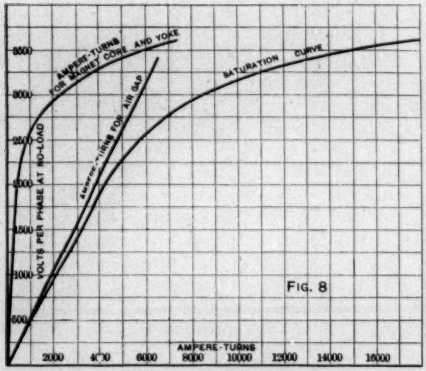


FIG. 8

FIG. 9

As there are 16 such 28-turn spools per phase, the reactance per phase is

$$16 \times 0.157 = 2.51 \text{ ohms.}$$

The reactance-pressure with full-load current of 98.5 amperes is

$$98.5 \times 2.51 = 248 \text{ volts}$$

From the saturation curve of Fig. 8, we find that 500 ampere-turns per field-spool are necessary for this pressure.

The demagnetizing ampere-turns equal (see Table III).

$$3 \times 0.77 \times 0.96 \times 1380 = 3050$$

Hence, one requires

$$3050 + 500 = 3550$$

†It is interesting to note that the end connections contribute more to the total inductance than the embedded length.

field ampere-turns per pole to generate full-load current in the short-circuited windings. The observed value was 3625 ampere-turns.

This agreement, within two per cent, is, of course, better than can be relied upon, or indeed than is at all necessary; but by this method it appears that an accuracy of from five to ten per cent is generally attainable in predetermining the excitation corresponding to a given short-circuit current.

We have checked the experimentally observed short-circuit current on 18 different machines and in 89% of all cases the agreement was within seven per cent. These are given in Table IV., which shows the agreement between calculation and experiment for seven single-phase and eleven three-phase machines, these being the only machines to which the calculation has been applied:—see next page.

An interesting point to be noticed in the short-circuit current relates to the very small value of the reactance-pressure as compared with that generally ascribed to such proportions. This arises from the elimination of all fluxes emerging from the armature, the remaining flux being, in our opinion, the only one correctly to be considered as pertaining to the reactance-pressure. Now, we should readily admit that with the data at present accessible, the determination of the inductance can only be very rough. But as it exerts so slight an influence upon the result, this inaccuracy in its predetermination is of less importance. In fact, it was the experimental observation that in a great number of machines examined, the short-circuit current deviated but slightly from that corresponding to a magnetomotive force equal to that of the field-spools, that led one of us in a series of articles in which he collaborated,* to neglect the inductance-flux as directly affecting the value of the resultant flux, and to employ it merely in deriving the angular distance between mid-pole position of the centre of one side of the armature coil, and the position corresponding to maximum value of the current in the armature coil. This theory gave very satisfactory results, on machines for low and medium saturation. But of course the present method which is supported by a sound theory, is preferable especially for high-saturation machines.

In the predetermination of the characteristic curves, one has frequent occasion to employ the following values:

*"Design of Alternators," *Engineering*, Vol. 70, p. 107.

TABLE IV.

Type of Machine.	Rated output in kw.	No. of Poles.	Periodicity (Cycles per Second.)	Ampere Turns on the Field Spool.		Percentage Deviation between Calculated and Observed Results.
				Observed.	Calculated from Short-circuited current.	
Single-phase Generator...	75	8	60	4000	4560	14
"	120	14	125	2900	2840	2
"	100	20	60	2875	3030	5
"	50	10	125	2900	2800	3
"	300	32	125	3650	3510	4
"	180	20	125	3250	3070	5.5
"	150	20	125	2950	2890	2
Three-phase generator, Y-connected...	360	12	60	3550	3880	9.3
"	300	12	35	5255	5050	4
"	225	6	25	6750	6300	7
"	150	14	60	3400	3500	3
"	150	12	60	4100	3940	4
"	75	20	25	4800	4900	2
"	250	24	25	7850	7930	1
"	100	12	60	3950	3900	1.5
"	150	12	60	3850	3850	0
"	250	16	60	3800	3800	0
"	200	48	40	5300	5550	5

Ohmic ($i\,R$) drop per ampere, 0.33 volts.
Reactance-pressure per ampere, 2.52 volts.
Demagnetizing ampere-turns per ampere $= 3\times0.77\times0.96\times14\times\sin\phi' = 31\sin\phi'$ (see Table III).
Distorting ampere-turns per ampere $= 3\times0.17\times0.96\times14\times\cos\phi' = 6.8\cos\phi'$ (see Table III).

CALCULATION OF THE ARMATURE INTERFERENCE FOR FULL LOAD AND COS $\phi = 1$.

In the diagram of Fig. 9, the vectors have the following magnitudes:

$$OE = 2880 \text{ volts.}$$

$$EB = 98.5\times2.52 = 248 \text{ volts.}$$

$$BA = 98.5\times0.33 = 32.5 \text{ volts.}$$

$$OA = \sqrt{(OE+BA)^2+(EB)^2} = 2915$$

Hence

$$\alpha = \sin^{-1}\frac{248}{2915}$$

$$= \sin^{-1}0.08$$

$$= 4.8°$$

The distorting ampere-turns equal $8.6\times98.5\times\cos\phi' = 670\cos\phi'$.

ϕ' is not yet determined, but it is evidently small—of the nature of 15°—and hence $\cos\phi'$ is approximately equal to unity and the armature distortion to 670 ampere-turns.

For 2915 volts per phase we see from the straight sloping line in Fig. 8. that the air-gap reluctance requires 5600 ampere-turns. Hence β which equals

$$\frac{\text{Distorting ampere-turns}}{\text{Ampere-turns for air-gap}}\times90°$$

is equal to

$$\frac{670}{5600}\times90° = 10.8°$$

$$\phi' = \alpha + \beta = 4.8° + 10.8° = 15.6°*$$

The demagnetizing ampere-turns

$$= 31 \times 98.5 \times \sin \phi'$$
$$= 31 \times 98.5 \times .262$$
$$= 800$$

From the saturation curve in Fig. 8 we find that 7900 ampere-turns are required for 2915 volts per phase. Hence the total field excitation required for full-load current of 98.5 amperes at unity power-factor, is

$$800 + 7900 = 8700$$

But at this increased magnetomotive force the leakage coefficient of the magnetic circuit has also increased, and at the high saturation values often met with in modern alternators this may amount to a very appreciable influence. We take account of it in our theory, though in the interests of simplicity, only in a roughly approximate manner, as anything approaching an exact estimation requires too much time† to be employed in practical designing work.

We adopt Hopkinson's definition for the leakage coefficient; namely,

$$\text{Leakage coefficient} = \frac{\text{Useful flux} + \text{leakage flux}}{\text{Useful flux}};$$

the leakage flux is equal to a constant $\times$ the ampere-turns per field-spool multiplied by

$$\frac{h\,(b+15)}{a} \text{ (see Fig. 10)}$$

for cores of rectangular cross-section and by

$$\frac{h \times b}{a}$$

for cores of circular sections.

The constant may be taken at about 1.7. It is

*If greater accuracy should be considered desirable, one could, now that a better approximation to ϕ' has been obtained, make a final precise calculation of β, as follows:

$$\beta = \frac{\cos 15.6°}{\cos 0°} \times 10.8°$$
$$= .963 \times 10.8°$$
$$= 10.40$$
and $\phi' = 4.8° + 10.4° = 15.2°$

†See Kapp's "Elektromechanische Konstruktionen," 1902, p. 28; Arnold, E. T. Z., 1902, p. 251.

assumed that pole-arc is between 0.55 and 0.70 of the polar pitch.

For no-load and 2915 volts per phase we obtain a leakage coefficient equal to 1.20.*

At full load the leakage coefficient increases to

$$1+0.20\times\frac{8700}{7900}=1.22$$

In Fig. 8 are plotted in addition to the right-hand curve of total saturation, two other curves, the intermediate one corresponding to the ampere-turns required for air-gap and teeth, and the left-hand curve corresponding to the ampere-turns required for magnet-core and yoke. For our purpose it has been sufficient to take the saturation for air-gap as a straight line through the origin tangent to the curve of total saturation, and to derive the curve for magnet core and yoke from the difference of the other two curves, taking into account the ampere-turns for the teeth at high saturation.

For a no-load potential of 2915 volts per phase (OA of Fig. 9), 1950 ampere-turns are, from the left-hand curve of Fig. 8, found to be required for magnet core and yoke. But so far as relates to the magnetomotive force required for magnet core and yoke, the increase in the leakage coefficient from 1.20 to 1.22 has the same effect as would result from an increase in pressure per phase from 2915 to

$$\frac{1.22}{1.20}\times 2915 = 2960 \text{ volts}$$

with constant leakage coefficient. From the left-hand saturation curve of Fig. 8 it is found that for 2960 volts, the magnet core and yoke would require 2050 ampere-turns.

$$2050-1950 = 100 \text{ ampere-turns}$$

is the increased excitation required for magnet core and yoke in virtue of the increased leakage coefficient.

From this we finally find that a total magnetomotive force of

$$8700+100 = 8800 \text{ ampere-turns}$$

---

*Ampere-turns per field-spool = 7650.

$h = 25$ $b = 37$ $a = 15$

$$\text{Total useful flux} = M = \frac{2915}{4.44\times 448\times 25\times 10^{-8}} = 5.8\times 10^{6}$$

$$\text{Leakage coefficient} = 1+\frac{1.7\times 7650\times 25\ (37+15)}{5.8\times 10^{6}\times 15} = 1.20$$

per field spool is required to obtain 5000 terminal volts (2880 volts per phase) for the full-load current of 98.5 amperes at unity power-factor.

To obtain the inherent regulation,* one compares the voltage per phase (2880) thus obtained, with the pressure corresponding to the same excitation at no load.

This is found from Fig. 8 to be 3030 volts, and the inherent regulation is therefore:

$$\frac{3030 - 2880}{3030} \times 100 = 4.9\%$$

In this manner the field ampere-turns have been estimated for various pressures and various amperes output and the results are plotted in Fig. 11. Experimental confirmation of the upper

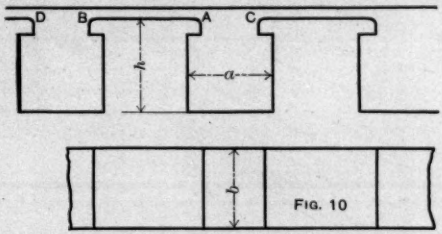


FIG. 10

curve (that for 2880 volts per phase) is found in the group of observed points plotted in Fig. 11 for these conditions of load and pressure. In Fig. 12 the right-hand saturation curve for full-load current of 98.5 amperes at unity power-factor has been derived by observation, while the plotted points are taken from the calculated curves of Fig. 11. The left-hand curve of Fig. 12 is merely the no-load saturation curve which has been reproduced from Fig. 8.

*We define the " inherent regulation " for a given power-factor as the percentage increase in pressure occurring when the load is decreased from rated full-load current to no load, the excitation remaining constant.

The " excitation regulation " is also a useful conception, and for a given power-factor is defined as the percentage increase in the excitation required to maintain constant terminal pressure, as the load is increased from no load to rated full-load amperes.

CALCULATIONS FOR COS $\phi = 0$,

For a power-factor of zero, the calculations become exceedingly simple. The armature distortion becomes equal to zero, but the demagnetizing ampere-turns have a great influence upon the results. The ohmic drop can be altogether neglected because of its vector position, while the reactance-pressure swings nearly into phase with the terminal pressure.

For full-load current of 98.5 amperes, the calculation is as follows (see Fig. 13):

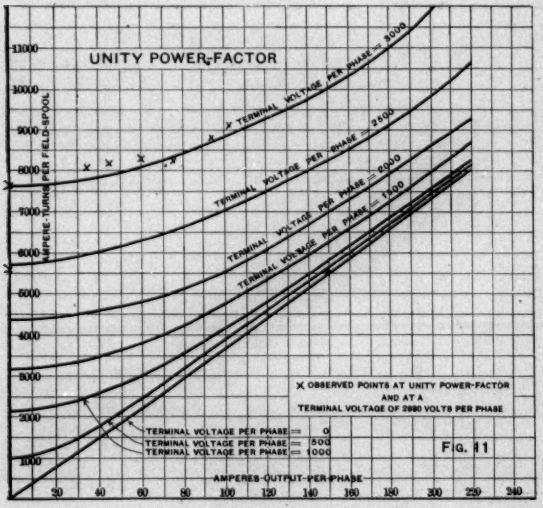


FIG. 11

$$EB = 248$$

$$OA = OB \text{ (approximately)} = OE + EB$$
$$= 2880 + 248 = 3128.$$

Demagnetizing ampere-turns = 3050

Ampere-turns per field-spool required to generate 3128 volts = 9400.

Total = 3050 + 9400 = 12450

$$\text{Leakage coefficient} = 1 + 0.20 \times \frac{12\,450}{9400} = 1.27$$

Increase in excitation required in virtue of increased leakage coefficient = 4100* − 3000 = 1100 ampere-turns.

Total excitation per field-spool required for 5000 terminal volts (2880 volts per phase), for 98.5 amperes output at $\cos \phi = 0$ is, therefore,

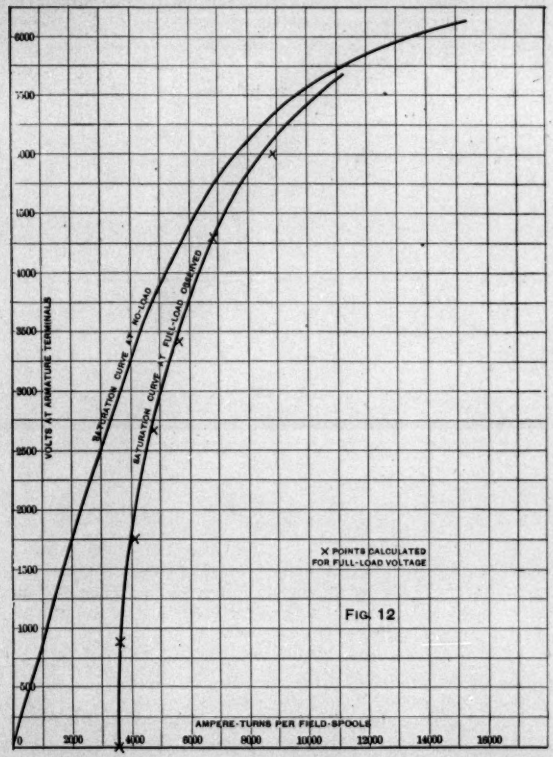


FIG. 12

*4100 and 3000 are the excitations for magnetic core and yoke corresponding respectively to $\frac{7.21}{1.20} \times 3128 = 3300$ and to 3128 volts.

$$12\,450 + 1\,100 = 13\,550 \text{ ampere-turns.}$$

Corresponding to the group of curves of Fig. 11 relating to $\cos\phi = 1$, there has been prepared for $\cos\phi = 0$, the group of curves shown in Fig. 14. Experimentally-observed points could, of course, not be obtained for $\cos\phi = 0$, but a number taken for values of $\cos\phi$ lying between 0.10 and 0.25 are given corresponding to the upper curve for 2880 volts; *i.e.*, 5000 terminal volts. These observed points lie somewhat below the calculated curve, and even when the difference in power-factor is taken into consideration, are slightly too low. This presumbly arises from the tooth-saturation which for these conditions reached 17 500 lines per square centimetre, and occasioned a slight decrease in the inductance, below the short-

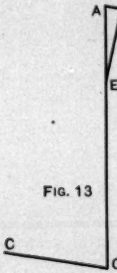


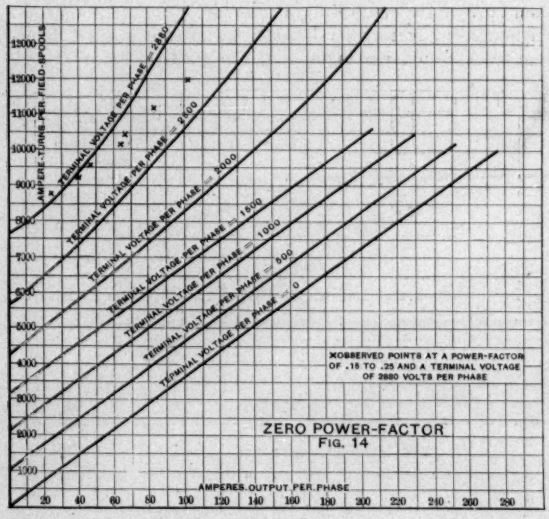
FIG. 13

circuit value, where the agreement was so excellent. The authors are not of opinion that a precise predetermination of the influence of the tooth-saturation is possible. Fortunately, also, the method, without consideration of the influence of the tooth-saturation on the inductance, gives much more precise results than are required in practice.

These groups of curves (Figs. 11 and 14), afford a simple means of deriving curves of the performance of an alternator under all conditions of load. Should one, for instance, wish to plot a curve showing the dependence of the terminal pressure on the current for constant field excitation, one draws a horizontal line corresponding to this constant value of the excitation, and the intersection of this line with the curves for different pressures, give at once sufficient points for plotting the desired curve. This

has been done in Fig. 15 for four different cases, for which experimental data were also available. This agreement is very close.

For values of the power-factor intermediate between zero and unity, one carries out the calculation in the same manner as has been illustrated for $\cos\phi = 1$. One employs for the purpose the vector diagram of Fig. 2, in order to calculate OA and the angle α it is preferable to employ the graphical method, taking the values directly from the diagram, and thus avoid the necessity


AMPERE-TURNS PER FIELD SPOOLS
AMPERES OUTPUT PER PHASE
TERMINAL VOLTAGE PER PHASE = 2880
TERMINAL VOLTAGE PER PHASE = 2500
TERMINAL VOLTAGE PER PHASE = 2000
TERMINAL VOLTAGE PER PHASE = 1500
TERMINAL VOLTAGE PER PHASE = 1000
TERMINAL VOLTAGE PER PHASE = 500
TERMINAL VOLTAGE PER PHASE = 0
XOBSERVED POINTS AT A POWER-FACTOR OF .15 TO .25 AND A TERMINAL VOLTAGE OF 2880 VOLTS PER PHASE

ZERO POWER-FACTOR
FIG. 14

for analytical calculations. β is obtained from the value of the armature distortion and one thus obtains

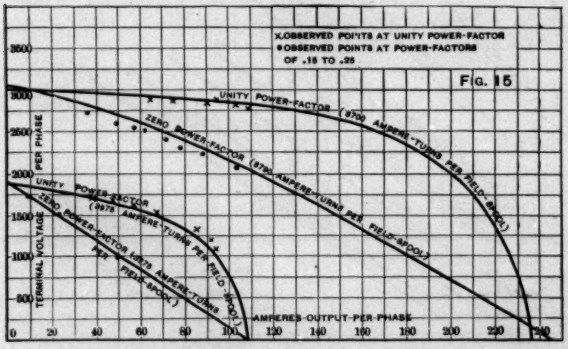
$$\phi' = \alpha + \beta + \phi$$

The remainder of the calculation proceeds in precisely the same manner as for $\cos\phi = 1$ and $\cos\phi = 0$.

The authors are of the opinion that in the course of time it will become customary to specify merely the regulation for a pure inductive load; for, just as in the calculations this was shown to be the simplest case to handle, so also is it in practice the case

which can be most cheaply, simply, and accurately experimentally determined.

For approximately unity power-factor, it is exceedingly difficult, even with the best of wattmeters and of other measuring instruments, to demonstrate the presence or absence of a slight difference of phase, and to measure it, although such a slight phase difference has a great influence on the regulation. For very low power-factors, *i.e.*, for $\cos \phi = 0$ as the limit, a phase difference of from 20° to 30° only slightly influences the result. Furthermore, for tests with $\cos \phi = 1$, a certain fall in speed is difficult to avoid when throwing on the load. For the same current at a low power-factor this difficulty in an experimental determination of the pressure regulation, is avoided.



All these factors tend to make the introduction of the percentage inherent regulation at $\cos \phi = 0$ as an important criterion of the design, a very desirable step. Should such a course be adopted generally, it would perhaps be necessary specially to consider those factors that may make the inherent regulation, at unity power-factor, poor, without impairing the inherent regulation at zero power-factor. These factors are:

1. The ohmic drop.

2. The ratio of pole-arc to pole-pitch. The influence of the ohmic drop amounts, in the design we have considered, to about 25% of the inherent regulation at $\cos \phi = 1$, and is negligible at $\cos \phi = 0$. Therefore it is necessary to specify the ohmic drop separately, and a resistance measurement with direct cur-

rent at the final temperature of the generator is quite sufficient for the purpose.

The ratio of pole-arc to pitch may have a decided effect, if quite abnormal dimensions are adopted; but inasmuch as other considerations, especially increased magnetic leakage, would prevent the use of a high ratio, the writers propose, for simplicity's sake, to disregard this factor. The writers put forward, therefore, the following specification as regards inherent regulation:

The generator shall, when loaded with the full rated current, lagging in phase behind the pressure by an angle corresponding to a power-factor of less than 0.2, at the temperature which the generator attains after 10 hours' full-load working, increase its normal pressure by no more than — per cent, when the load is thrown off, the excitation remaining constant.

The ohmic drop, calculated with rated full-load current, and a resistance determined experimentally at the final temperature with direct current, shall not amount to more than — per cent.

The calculation of these data may be briefly repeated in tabular form:

Output at unity power-factor	850 kw.
Type of winding	Y
Pressure per phase	2880
Amperes per phase at full load	98.5
Number of armature-turns per phase	448
Number of poles	32
Number of armature-turns per pole and per phase	14
Number of effective armature ampere-turns per pole and per phase	1380
Ratio of pole-arc to pole-pitch	0 63
Space taken by one side of the winding, per pole and per phase in per cent. of pole-pitch	33%
Breadth factor (B)	0.95
Demagnetizing ampere-turns per ampere	31
Demagnetizing ampere-turns at full load (a)	3500
Number of slots	192
Number of slots per pole and per phase	2
Depth of slot (D)	9.2 mm.
Depth of slot above winding space (d)	1.2 "
Width of slot at the root	3.3 "
Width of slot at the end	3.3 "
c.g.s. lines per ampere-turns per cm. length of winding in one slot	1.99
Total lines per cm. length of winding in one slot	1.99

c.g.s. lines per ampere-turn per cm. length of effective winding	1.00
c.g.s lines per ampere-turn per cm. length of free winding	0.7
Length of one turn in iron (effective length)	55 cm.
Length of one turn in air (free length)	106 "
c.g.s. lines per ampere-turn due to effective length of a turn	55
c.g.s. lines per ampere-turn due to free length of a turn	74
c.g.s. lines per ampere-turn	129
Inductance of one coil	0.001 henrys
Reactance of one coil	0.157 ohms
Reactance of all coils per phase	2.51 "
Reactance-pressure per ampere	2.51 volts
Reactance-pressure per phase at full load	248 "
Total internal pressure	3128 "
Ampere-turns required for internal pressure (A)	9400
Demagnetizing ampere-turns (a)	3050
$A+a$	12450
Shape of magnet cross-section	rectangular
Width of magnet	37 cm.
Radial length of magnet core	25 "
Smallest distance between magnet cores midway along their length	15 "
Leakage c.g.s. lines corresponding to internal pressure	$= 1.24\times10^6$
Useful flux	6.2×10^6
Leakage coefficient	1.20
Leakage coefficient corresponding to internal pressure ampere-turns + demagnetizing ampere-turns	1.27
Ampere-turns for (field+ yoke) corresponding to internal pressure	3000
Ampere-turns for (field+ yoke) corresponding to the increased leakage factor	4100
Difference in ampere-turns (C)	1100
Ampere-turns for internal pressure	9400
Demagnetizing ampere-turns ... (a)	3050
Total ampere-turns at full load ... ($\beta + A + a$)	13550
Internal pressure (E) corresponding to total calculated ampere-turns at no load	343 volts
Inherent regulation at zero power-factor	23%
Inherent regulation at power-factor up to 0.20 (estimated)	21%
Length of one turn	1.61 cm.
Total length of the turns of one phase	720 "
Cross-section of one conductor	44.2sq. "
Cross-section of all parallel conductors	44.2 " "
Resistance of one phase at 60°	0.33 ohm.
Ohmic drop per phase per ampere	0.33 volt
Ohmic drop per phase at full load	32.6 "
Ohmic drop in per cent. of pressure per phase	1.13%

APPENDIX.

Derivation of the tables set forth in Table I., and consideration of the general solution for any wave-form of electromotive force and current.

We have considered the case of armature interference due to a single conductor per pole, traversed by a constant current of i amperes, the conductor occupying a fixed position opposite the pole. (See Figs. 3 to 6.) But of course the occurrence in a dynamo consists in the flow of an *alternating* current in the conductor, and the conductor moves past the pole at a rate corresponding to the frequency of this alternating current. Hence the amount of the interference of the armature magnetomotive force instead of being constant, varies from instant to instant. The magnetic flux will tend to respond to these variations in the armature magnetomotive force, but in so far as it responds it generates eddy currents, so that the amplitude of these periodic variations in the magnetic flux is very small in comparison with the amplitude of the periodic variations in the total magnetomotive force. Thus it is justifiable to assume a mean magnetic flux corresponding to the mean total magnetomotive force. For various symmetrically situated positions of the conductor, we calculate the armature interference in the manner already illustrated and take a mean of these results for the final value. We shall now explain the derivation of this mean value for the case of a single-phase alternator with one slot per pole, on the assumption of a sine curve of current.

If we let the slot contain $2n$ conductors, we have n ampere-turns per pole. Letting i denote the effective armature current then evidently:

$n i \sqrt{2}$ = maximum armature ampere-turns per pole. Let us subdivide the pitch into 10 sections corresponding to the values

$$x = 0, \qquad x = \frac{\tau}{10}, \qquad x = 2\frac{\tau}{10}, \text{ etc.},$$

and let us first consider the case where maximum current is reached when the conductor reaches mid-pitch position. One sees at once that in this case the total number of magnetic lines is not affected by the armature interference, *i.e.*, the *demagnetizing* ampere-turns are equal to zero. Hence, in our formula (see page 188 and footnote).

$$y = \tfrac{1}{2}\frac{x\,(b-x)\,i}{A\,b - (i\,b/2) + x\,i}$$

Since we have $2n$, conductors for every one conductor of the elementary case, the formula now reads,

$$y = \tfrac{1}{2} \frac{x\,(b-x)\,i \times 2n}{A\,b - n\,i\,b + 2\,x\,i\,n}$$

or, reduced

$$y = \frac{x\,(b-x)\,i\,n}{A\,b - n\,i\,b + 2x\,i\,n}$$

the denominator, which as we have seen represents the entire surface, remains constant. In order to derive the average value of the armature *distortion* we have only to consider the variable numerator.

$$x\,(b-x)\,i\,n$$

The calculation can best be arranged in tabular form and this is done in Table A for the case of 50% pole-pitch, n turns per pole and one slot per pole.

TABLE A.

CALCULATION OF ARMATURE DISTORTION FOR THE CASE OF A UNI-SLOT ALTERNATOR WHERE MAXIMUM CURRENT IS REACHED WHEN THE CONDUCTORS OCCUPY THE MID-POLE POSITION.

Ratio of Pole-arc to Pitch Equals 50%

Distance from Centre of the Armature Magnetomotive Force to Mid-pole Position equals 0.

x Distance of group of conductors from pole-tip	$b - x$	Magnetomotive force in ampere-turns, of one group of conductors, at different positions.	$x\,(b-x)\,i\,n$ [the product of the values in the first three colums.]
0	$5\,\tau/10$	$n\,i\sqrt{2} \times 0.71$	0
$\tau/10$	$4 \times \tau/10$	$n\,i\sqrt{2} \times 0.89$	$n\,i\sqrt{2}$ 3.55 $(\tau/10)^2$
$2 \times \tau/10$	$3 \times \tau/10$	$n\,i\sqrt{2} \times 0.99$	$n\,i\sqrt{2}$ 5.92 $(\tau/10)^2$
$3 \times \tau/10$	$2 \times \tau/10$	$n\,i\sqrt{2} \times 0.99$	$n\,i\sqrt{2}$ 5.92 $(\tau/10)^2$
$4 \times \tau/10$	$1 \times \tau/10$	$n\,i\sqrt{2} \times 0.89$	$n\,i\sqrt{2}$ 3.55 $(\tau/10)^2$
$5 \times \tau/10$	$0 \times \tau/10$	$n\,i\sqrt{2} \times 0.71$	0

In Table A the distorting effect of the component group of conductors when lying under the pole-face has been estimated. It

has already been mentioned that the conductors when not lying under the pole face, exert no distorting influence; hence we obtain the average value for

$$x\,(b-x)\,n\,i$$

by adding together the six values in the last column of Table A, and dividing by 10, the total number of sections into which the pitch, τ, has been subdivided.

This average value is

$$1.9\,i\,n\,\sqrt{2}\,(\tau/10)^2 = 0.027\,i\,n\,\tau^2$$

The magnetic centre has therefore been shifted by the amount

$$y = \frac{0.027\,i\,n\,\tau^2}{A\,.\,b}$$

$$= \frac{0.027\,i\,n\,\tau^2}{0.5\,A\,\tau}$$

$$= 0.054\,(\frac{i\,n}{A})\,\tau$$

We must next proceed to consider the case where the centre of the group of armature conductors is at a distance $\tau/10$ from the pole centre at the instant when maximum current flows. Thus it now becomes necessary to consider the alteration not only in the form of the flux distribution but also in its amounts.

The change in magnitude; *i.e.*, the armature demagnetization, is dependent upon the expression

$$(b-2\,x)\,n\,i^*$$

With reference to Table A we have stated that the conductors only cause a distortion of the field when lying under the pole face, and have hence considered only these positions of the conductors in estimating the distortion. But in estimating the decrease in the total flux, armature conductors in all positions have to be taken into account. One sees this best by considering Fig. 6 and 10. x is taken as positive in the direction from A to B. (Fig. 10). We may integrate from C to B or from one to the next of any other two points separated from one another by a distance equal to the pitch. In all cases where these conditions are complied with, the same result will be obtained. The plan pursued in deriving the following Tables has been to integrate between points C and B. $b\,i$ is derived by

*$(b-2x)\,n\,i$ is the area by which the original area $A\,b$ is diminished by the armature demagnetization This is evident from Fig. 5.

calculating the mean magnetomotive force in ampere-turns exerted by the armature conductors in moving from B to C.

$B\,C$ is divided into 10 parts and as we know that the maximum value of the sine wave of current occurs when the conductor is distant by $\tau/10$ from the mid-pole position, one can readily derive the corresponding values for all the other positions and thus obtain the mean value, which is

$$0.400\ (i\ n)\ \tau$$

The value $2\ x\ n\ i$* must of course also be obtained from the mean of this same range of positions, *i.e.*, from B to C, x being taken as positive in the direction $A\ B$ from A. But the influence of the conductors when lying between A and C is evidently zero, since the air-gap may be taken as infinitely great. Hence, we have, just as in Table A, to consider only the conductors lying directly under the pole-arc.

So we again take ten symmetrically-situated positions, of which only the values for the five lying between A and B need to be calculated, while in the remaining positions

$$2\ x\ n\ i = 0$$

TABLE B.

CALCULATION OF $2\ x\ n\ i$ IN OBTAINING THE ARMATURE DEMAGNETIZATION FOR THE CASE WHERE MAXIMUM CURRENT IS REACHED WHEN THE CONDUCTORS OCCUPY A POSITION DISTANT BY $\tau/10$ FROM MID-POLE POSITION.

x Distance of group of conductors from mid-pole position	Magnetomotive force of one group of conductors, in ampere-turns, at different positions.	$2\ x\ n\ i$, *i.e.*, the product of the values in the first two columns.
0	$i\ n\sqrt{2}\times 0.89$	0
$\tau/10$	$i\ n\sqrt{2}\times 0.99$	$0.099\sqrt{2}\ (n\ i)\ \tau$
$2\ \tau/10$	$i\ n\sqrt{2}\times 0.99$	$0.198\sqrt{2}\ (n\ i)\ \tau$
$3\ \tau/10$	$i\ n\sqrt{2}\times 0.89$	$0.267\sqrt{2}\ (n\ i)\ \tau$
$4\ \tau/10$	$i\ n\sqrt{2}\times 0.71$	$0.284\sqrt{2}\ (n\ i)\ \tau$
$5\ \tau/10$	$i\ n\sqrt{2}\times 0.455$	$0.227\sqrt{2}\ (n\ i)\ \tau$

*i.e., $2x$ (armature ampere-turns per pole).

A summation of the values in Table B gives us

$$1.36\ (n\ i)\ \tau$$

Hence, the mean value of $2\ x\ n\ i$ is

$$\frac{1.36\ (n\ i)\ \tau}{10}$$

$$= 0.136\ (n\ i)\ \tau$$

and we at once obtain the distortion as

$$(b - 2\ x)\ n\ i = 0.400\ (n\ i)\ \tau\ 2\ x\ 0.136\ (n\ i)\ \tau$$
$$= 0.128\ (n\ i)\ \tau$$

The shifting of the magnetic centre (*i.e.*, the armature distortion) is calculated just as in Table A, and as it is only the final results which are of interest this calculation will not be repeated here. The results of these calculations are brought together in Table C.

TABLE C.

POLE ARC = 50 PER CENT OF PITCH.

ϕ' Distance from pole centre to the position where the current in the armature coil is a maximum	Decrease in flux expressed by $(b - 2\ x)\ n\ i$ *i.e.*, the armature demagnetization.	$0.41 \sin\phi'$	Amount of shifting of centre of magnetic flux expressed by $x\ (b - x)\ n\ i$ *i.e.*, the armature distortion.	$0.027 \cos\phi'$
0	0	0	$0.027\ (i\ n)\ \tau^2$	0.027
$\tau/10$	$0.128\ (i\ n)\ \tau$	0.127	$0.0254\ (i\ n)\ \tau^2$	0.0256
$2\ \tau/10$	$0.24\ \ (i\ n)\ \tau$	0.241	$0.0217\ (i\ n)\ \tau^2$	0.0219
$3\ \tau/10$	$0.33\ \ (i\ n)\ \tau$	0.331	$0.0158\ (i\ n)\ \tau^2$	0.0159
$4\ \tau/10$	$0.39\ \ (i\ n)\ \tau$	0.404	$0.0079\ (i\ n)\ \tau^2$	0.0084
$5\ \tau/10$	$0.41\ \ (i\ n)\ \tau$	0.41	0	0

As one sees from the table, the agreement with the sine curve is practically perfect, and we are fully justified in drawing the conclusions expressed in the two following equations:

$(b - 2x)\ n\ i = 0.41\ (n\ i)\ \tau \sin\phi'$ = armature demagnetization.

$x\ (b - x)\ n\ i = 0.027\ (n\ i)\ \tau^2 \cos\phi^2$ = armature distortion.

In the same way the corresponding values for a pole-arc equal to 70% of the pitch, have been found to be

$(b - 2\ x)\ n\ i = 0.52\ (n\ i)\ \tau \sin\phi'$ = armature demagnetizaton.

$x\ (b - x)\ n\ i = 0.0707\ (n\ i)\ \tau^2 \cos\phi'$ = armature distortion.

We have now arrived at the stage where we may drop the original assumption of a magnetic material without reluctance, and we will examine into the alterations thereby involved: up to this point we have reckoned throughout on the basis of the magnetic flux having only to cross the air-gap, so far as relates to the reluctance encountered. Now, those magnetic lines which must also traverse magnet core and yoke will thereby have to encounter a much greater reluctance than we have up to this point assumed.

Much the simplest way of taking account of this influence, is to alter the expressions from magnetic flux to magnetomotive force. It should be observed that this only applies to that portion of the magnetic flux which traverses magnet and yoke; for that portion which only brings about a shifting of the magnetic field the retention of the magnetic lines is correct. Nevertheless, in order to preserve uniformity in expression we shall also transfer the latter into equivalent magnetomotive force, employing, *not* the total field magnetomotive force A but the magnetomotive force A^1 (in ampere-turns), which is necessary to drive the magnetic flux across the air-gap. That portion of the armature magnetomotive force which acts to change the magnitude of the magnetic flux is denoted by armature demagnetization, and that which acts to change its position, by armature distortion.*

Returning now to the example which we have been considering, we have

Armature demagnetization (for $b = 0.5\ \tau$) $= 0.82\ (i\ n) \sin \phi'$
" " (for $b = 0.7\ \tau$) $= 0.75\ (i\ n) \sin \phi'$
" distortion, (for $b = 0.5\ \tau$) $= 0.108\ (i\ n) \cos \phi'$
" " (for $b = 0.7\ \tau$) $= 0.202\ (i\ n) \cos \phi'$

While the armature demagnetization must be deducted directly from the field magnetomotive force, one employs the armature distortion to determine the displacement of the magnetic centre, expressing this either in the form:

$$y = \frac{\text{Armature distortion}}{\text{Gap ampere-turns}} \times \tau/2$$

or in degrees:

$$\beta = \frac{\text{Armature distortion}}{A^1} \times 90°$$

or,

$$\beta = \frac{\text{Armature distortion}}{\text{Gap ampere-turns}} \times 90°$$

*The term " Armature Distortion " as employed in this paper involves a different conception from that heretofore associated with the term. It has always been a very vague expression. Real physical significance attached only to the angle β.

DISCUSSION ON "CONTRIBUTION TO THEORY OF THE REGULATION OF ALTERNATORS" AND "THE MECHANICAL CONSTRUCTION OF REVOLVING-FIELD ALTERNATORS."

C. A. ADAMS, JR.:—Owing to the difficulty of checking the specified regulation of a large alternator by direct test, many efforts have been made to devise an indirect test which shall be reliable, simple, easily applied under shop or installation conditions, and shall involve the least possible calculation.

The two [1] methods most commonly used during recent years fairly satisfy all these conditions except the first, which is the most important, and which, as has already been pointed out, they do not at all satisfy except with particular types of machines. They both require the observed saturation and short-circuit curves.

The method of which the above named are special cases, called by the speaker the General Method,[2] requires the same two observed curves, involves considerably more computation, but is far more reliable.

Behrend's method of opposing the two halves of the field with unequal currents is ideal in many respects, although the speaker has not as yet tested it experimentally. Its application, however, appears to be limited to machines with a large number of poles, although some method of correcting the error due to a small number of poles may be devised. This method is obviously inapplicable to any of the machines with single field-coil.

The method of Messrs. Hobart and Punga requires only the saturation curve, and is otherwise a complete predetermination involving a very considerable amount of calculation. From the single example given by the authors, it appears to give good results as a means of determining the excitation and regulation. This is, however, a very narrow experimental foundation, and the speaker would like very much to see the method applied to other types of alternators. Even though this method should fulfil all of the author's expectations, it is nevertheless decidedly unsuitable as a check on specified regulation, since it is primarily a method for predetermination, a method for the designing engineer. It takes account of one generally neglected factor, the effect of the ratio or pole arc to pole-pitch, and gives a very interesting method of analyzing armature reaction, an objection to which, however, is the "cut and try" process involved in its application.

There are several statements which require special attention.

1. The authors start out by assuming that all other methods give inaccurate results for "different types of machines."

1. The e.m.f and m.m.f. methods, or, as Mr. Behrend has most appropriately called them, the pessimistic and optimistic methods.

2. *Harvard Engineering Journal*, 1902–03. The speaker makes no claim to originality in this method, as it is the direct application of the methods of analysis used in connection with transformers and induction motors for at least ten years.

The method referred to above as the "General Method" has been in use by the speaker for several years and has been applied to a variety of types. In no case where the experimental data were reliable, have the observed results differed in an important degree from those calculated by this method. The types tested include revolving field, inductor, and a machine with a closed coil, three-phase armature. This last was a very trying case, owing to the three-belt armature winding, each belt occupying 120 electrical degrees of the armature surface.

Some of the results referred to are given in the accompanying table taken from the *Harvard Engineering Journal* for April, 1903. Column *A* gives observed results; B, calculated by "General Method"; C, e.m.f. method; and D, m.m.f. method. Machine No. 1 is a G. E. 50-kw. revolving-field alternator with

Machine.	Non-inductive Load.								
	Full Load Excitation.				Regulation %.				Power-Factor.
	A	B	C	D	A	B	C	D	
No. 1	15.1	15.4	15.7	15.2	9.8	10.5	12.7	10.1	.8
No. 2	150	149.5	171	147.3	4	3.9	8.4	3.4	.8
No. 3	80.8	79.5	87	72.6	7.4	7	9.8	3.9	.8
No. 4	—	—	—	—	—	—	—	—	.9
No. 4	132	139	197	131	4	5	12	3.8	.7
No. 5	141	139 5	146	134.5	5.5	5	7.3	3.9	.85
No. 6	2 99	2 97	3.07	2.89	23.8	23.5	25.9	21 05	.75

Machine.	Inductive Load.								
	Full Load Excitation.				Regulation %.				Power-Factor.
	A	B	C	D	A	B	C	D	
No. 1		20	24.5	19.6		31.5	46	31	.8
No. 2		200	350	181.3		14.5	36.2	10.1	.8
No. 3		146	250	84		24.5	36.3	8.6	.8
No. 3	108	107	127.5	76.5	19.3	18.8	23.8	8.4	.9
No. 4	200	206	400	158	14.8	15.5	49	9.1	.7
No. 5	168	169	220	146	13.6	14.	23	6.8	.85
No. 6	3.89	3.91	4.52	3 58	46.6	47.	57.5	39.5	.75

practically no saturation; No. 2 is a G. E. 1500-kw. revolving-field alternator with moderate saturation; No. 3 is a 750-kw. Stanley inductor alternator with high saturation; No. 6 is the closed-coil machine mentioned above; No. 4 and No. 5 are European machines the data for which were taken from published tests. In the other cases the tests were made with great care under the personal supervision of the speaker. It is not claimed that this method is theoretically as sound as that of Messrs. Hobart and Punga, but simply that it does give good results.

2. The authors claim on the first page of their paper that their method is free from hypothetical assumptions is doubtless intended only as a relative claim, since they have eliminated only one or two of the numerous assumptions and approxima-

tions ordinarily made use of to simplify this naturally complex problem. One assumption which has a particular bearing on this method is that the air-gap is constant under the whole pole-face, which is often not the case, the pole pieces being backed off at the edges in order to produce a desired wave shape. The result of this is to reduce the effective pole width by an amount only determinable by laborious calculation.

3. The authors have placed cross-magnetization where it belongs, although the same end is obtained vectorially with much less trouble and a little less theoretical accuracy in the "General Method."

4. The relative importance of the leakage reactance as compared with the armature m.m.f. is somewhat underestimated by the authors, at least the example given is not an average one in this respect. This relative importance is measured by the ratio, at short circuit, of field m.m.f. to armature m.m.f., which is from the example given, 1.16. The speaker has worked this out for a number of typical cases, where it was found to vary from 1.1 to 2, the highest values occurring in inductor alternators.

5. The author's suggestion as to specifying regulation at a low power-factor rather than at power-factor = 1, is in accord with opinions expressed in these meetings, and points to Mr. Behrend's field-bucking method as the best check in the case of large, many-pole alternators.

Remembering that it is the wattless component of the cusrent which has the greatest effect upon regulation, the following table makes very clear the reason why a small deviation of the power-factor from unity makes such a great difference in the regulation, whereas a considerable deviation from zero makes practically no difference.

Power-factor	0.995	0.99	0.98	0.90	0.20	0.10
Wattless component	0.10	0.14	0.20	0.435	0.98	0.995

B. A. BEHREND:—We designing engineers, and men in charge of manufacturing concerns, receive specifications from the consulting engineers, which call for a regulation of say, 6, 7, 8, 9, 10, or 11% on a power-factor of 100%. Who among you has ever made a test on a large unit on a power-factor of 100%? The speaker has never had the pleasure of being able to get 1000 kilowatts of load with a 100% power-factor. Experiments of this nature are confined to small units of 100 or 200 kw. in which the load may consist of German-silver strips wound non-inductively. A water load is a load which may have considerable electrostatic capacity. This was pointed out 30 years ago by a venerable German teacher, Professor F. Kohlrausch, by passing an alternating current through an electrolyte. Now, if there is a very small electrostatic capacity, there is a small leading current, and a small leading current represents a current magnetizing the armature, and you may say after your test is made that the

machine is the best you ever saw—that the regulation is 3.5%, while we know it is 7%. This is also the reason why it has often been said that the regulation of the inductor type of alternator is so satisfactory, because when it is tested on a water load it is easy to obtain excellent regulation. Tests on large units at 100% power-factor are a farce. It is next to impossible to measure accurately a power-factor at 100% and we therefore have to confine ourselves to the determining of the regulation under conditions which can be determined by actual experimental test. Such tests can be made on a power-factor of zero at which the regulation can be actually measured. By using two machines, one as a synchronous motor and one as generator, such regulation tests can be obtained. The speaker indicated half a year ago how, by splitting the fields, such regulation curves may be obtained on a single machine, and fairly accurate regulation and heating data may be secured. More and more, prominent engineers seem to realize the importance of a regulation at low power-factors, as has been indicated since reading the writer's paper a year ago, by expressions from Mr. W. L. Waters, and now from Messrs. Hobart and Punga. But the regulation on zero power-factor does not give the regulation on 100% power-factor, even if, as Mr. Hobart says, you specify the ohmic drop, and the ratio of pole-arc to pole-pitch, as you may shape the saturation curve so that you get, for instance, a regulation of 5% on purely inductive load, and a regulation as poor as 10% or as good as 4% on non-inductive load.

It appears to be wise to admit the existing dilemma. The question of accurately determining the regulation of alternators cannot be solved. Many questions in natural science are not capable of an accurate solution. Let us acknowledge our ignorance instead of trying to deceive one another that we know something which we do not know. It seems to the speaker far more dignified and more in accordance with the science that we are working in, to say that this case is so complex, so intricate, there are so many factors to be taken into account, that it can no more be solved than you can state to one-thousandth of an inch the distance between two chalk marks drawn on the floor.

W. L. WATERS (*by letter*):—This theory of the regulation of alternators hardly seems to possess that freedom from hypothetical assumptions that Mr. Hobart claims for it. Mr. Hobart commences accurately enough by classifying the self-induction lines linked with the armature winding into three groups;—the lines across the slot itself, the cross-magnetization lines, and the back-magnetization lines. But he then makes the statement that it is more accurate to neglect the cross magnetization lines as they have practically no resultant effect. Mr. Hobart has apparently confused the variation of the armature self-induction lines, due to the rotation of the magnets

with the variation of those lines as the armature current follows a sine function all the time. In considering the cross-magnetization lines, Mr. Hobart considers them as being fixed relatively to the pole piece and swept across the armature conductors, as the pole piece moves past them. He seems to forget that these lines are an integral part of the self-induction proper of the armature, just as much so as those lines linked only with the slot and that often they form the greater part of the armature self-induction lines.

Some years ago while working on the question of regulation of alternators, the writer made numerous experiments, measuring the self-induction of alternator armatures under various conditions. And the following figures taken from the tests on a large number of machines show very well the proportion that these cross-magnetization lines bear to the total self-induction lines in standard alternators.

The table gives the self-induction per unit length of the armature. " A." when the armature stands alone, the magnets not being in position, and " B," when the magnets are in position and the armature winding opposite the center of the pole face.

No.	Machine.	Self-Induction of Armature. Position " A "	Position " B "
1	300-kw. 60-cycle	34	60
2	450-kw. 60- "	59	93
3	500-kw. 50- "	78	120
4	50-kw. 40- "	35	78
5	75-kw. 50- "	24	50
6	400-kw. 60- "	38	94

Position " A " gives practically the self-induction of the slots alone, while position " B " gives the self-induction of the slots and the cross-magnetization lines. It will be seen that the total self-induction of the coils averages about double that due to the flux in the slots alone.

At the time of making the above tests, the writer tried calculating the regulation of these alternators on non-inductive load by figuring the self-induction e.m.f. from the self-induction given in position " B " and simply taking this e.m.f. in quadrature with the main armature e.m.f. A comparison of the calculated and actual test results are given in the following table:

Machine.	Regulation Per Cent. Actual Test.	Calculation.
No. 1	7.4	8
2	6.1	5.2
4	9.4	8.3
5	8.7	8.5
6	7.0	7.1

The method appears to give fair results. But it is very evident that, if in addition, we tried to take into account the back ampere-turns on the armature, the calculated results would differ greatly from the actual test figures. And if the

cross magnetization was taken into account by Mr. Hobart on the 850-kw. alternator he describes, the calculated and test regulations would show a wide discrepancy.

Mr. Hobart's method should be added to the list of empirical methods and when the various coefficients have been determined by experiments on a number of machines, it will probably be capable of giving good results in practice. The calculation of the short-circuit current of an alternator cannot be considered as a test of any theory. A single coefficient to give the armature reaction effect is all that is required, and this coefficient varies only very slightly with the different standard commercial designs, so that the short-circuit current is the simplest calculation to make in connection with an alternator. The real test of any theory is to calculate the regulation of an alternator on inductive loads. In connection with this the writer thinks Mr. Hobart is doing service in again emphasizing the advisability of guaranteeing regulation on a low power-factor, preferably on power-factor zero, rather than on non-inductive load.

Probably the most important point in Mr. Hobart's theory is the way in which he takes into account the effect of the increased leakage caused by the back ampere-turns on the armature. This increased leakage has been mentioned before as being detrimental, but this is the first time that any method of calculating the effect has been published. Mr. Hobart deserves due credit for emphasizing this point.

C. A. ADAMS, JR.:—The speaker wishes to take exception to the last statement in Mr. Waters' communication. The method employed by Messrs. Hobart and Punga for taking account of the extra leakage was described by the speaker in detail in the *Harvard Engineering Journal*, November, 1903; and January, 1904. Even the approximate method of getting the air-gap line by drawing a tangent to the lower end of the saturation curve was there explained.

B. A. BEHREND:—The speaker wishes to take this opportunity to make good a sin of omission of which he feels guilty in connection with his paper presented a year ago. Professor Alexander Potier published some four years ago a theory based on tests on alternators, which the speaker placed at his disposal, which is substantially the same as that suggested by Professor Adams,—the one used in the speaker's paper and the one which it is believed has found its way into almost all the calculations of designing engineers; namely, the splitting of the armature reaction into two components, one pure reaction and the other pure reactance. The speaker wishes to go on record as giving Professor Potier credit for his part in this work.

GANO S. DUNN:—In the absence of the authors, Mr. Dunn presented the paper by Messrs. Hobart and Punga and called attention to points which he thought they would wish to make were they present. He said in answer to Mr. Waters' discuss-

ion that as he read the paper, the authors did not take the position that the lines linked with the armature conductors, never emerging from the armature, following path *l*, are really the only lines that should be included in the calculation of the armature's inductance. Hobart and Punga's paper said:

"An interesting point to be noticed in the short-circuit current relates to the very small value of the reactance pressure as compared with that generally ascribed to such proportions. This arises from the elimination of all fluxes emerging from the armature, the remaining flux being in our opinion the only one correctly to be considered as pertaining to the reactance pressure."

This would mean, taken in connection with statements later in the paper, that the authors are willing to admit that the calculation of the absolute inductance of the armature by itself should not be limited to the lines in path *l*. In the present method of determining the regulation of machines, the lines in the other two paths are merely not classed as self-inductive but as distortive. They are not neglected, however, but are taken care of in the calculation of the distortion constant.

In response to Mr. Behrend's remarks in regard to the necessity for including the degree of saturation of the magnetic circuits as a factor in the problem of regulation, Mr. Dunn pointed out that although not considering this as important a factor as did Mr. Behrend in his paper on the subject, they had included it as could be seen by reference to Fig. 14 where the excitation curves were given for a large number of particular pressures.

Mr. Dunn expressed appreciation of Mr. Behrend's views in his book on induction motors, and also as given verbally to the meeting, to the effect that engineering and designing of the kind under discussion, was not a science but an art. It required the consideration of innumerable factors, many of which were human rather than mathematical, and one should go at the business of designing without being too tightly hampered by purely physical or purely mathematical considerations.

Mr. Dunn inquired in reference to Mr. Rushmore's paper, whether the author had ever used and whether he approved elastic spokes for holding the revolving rings of generators—a spoke that permits the bursting strain to be taken by the ring as an annulus and not by the spokes in longitudinal tension.

DAVID B. RUSHMORE:—In reply to Mr. Dunn's question the speaker would say that most of the high-speed machines which have been shown this evening are so constructed that the rims are self sustaining, the purpose of the dove-tails and arms being simply to drive the outer rim. These rims are built up of laminated steel sheets riveted together.

The regulation of alternators is a very important subject, both to the designer and to the operator. The importance comes not so much as a question of what change in pressure

will take place under certain conditions, as it does with regard to the necessary change in exciting conditions to sustain the pressure under these varying loads and power-factors. Unless a large margin is left in the generator field rheostat or in the exciter pressure, and the iron is worked well below the knee of the saturation curve, it is necessary to predetermine the relations which will hold in the generator between the exciting current and the exciting pressure and the pressure, current, and power-factor of the armature load. It may be of interest to state that the regulation of alternators can now be predetermined for all conditions within the limit of commercial necessities.

It is possible that the speaker does not quite understand Mr. Behrend's remark about obtaining the actual regulation of an alternator of large output at unity power-factor, but a short time ago the actual regulation at unity power-factor and at other power-factors, both lagging and leading, was obtained on a generator of 3500-kw. output. In this particular case the actual results were in very close agreement with the estimated values.

GANO S. DUNN:—Replied that the spoke Mr. Rushmore described was not an elastic spoke, but a loose one, and said he had found such a construction bad, especially in the case of a laminated ring, because it was impossible to shrink the ring on or in other ways to make it fit the spokes tightly, and there was in consequence considerable play as a result of the clearance necessary in assembling. When the centrifugal forces came into play this clearance made the ring slightly loose on its spider, and this slight looseness increased with wear, with very bad effects. The elastic spoke referred to was for the object of permitting the ring to yield away from the center a slight amount sufficient for it to take up its own strain and yet to keep it sufficiently rigidly bound to the hub to avoid looseness.

F. A. C. PERRINE:—Mr. Rushmore showed one picture in which that was described exactly. It was a revolving field which had a smooth, uniform rim bolted to spokes with extended ends; the spider construction not being continuous. These rims are bolted to the spoke with a bolt that is capable of extension so arranged as to produce the elastic spoke which Mr. Dunn has spoken of. This theory was discussed about four or five years ago in connection with some high-speed water-wheel plants, and the bolt construction was adopted at that time.

BRADLEY T. MCCORMICK (*by letter*):—In considering the subject of regulation of alternators, it may be of interest to note a simple graphic method by which the regulation for any current and power-factor can be obtained, when the saturation curve is given and the load characteristic for the same value of current at zero power-factor.

Fig. 1 is a vector diagram of an alternator, which hardly needs explanation.

E = terminal pressure.
V = pressure to which machine would rise if the load were removed.
L = inductance drop.
R = resistance drop.
A = drop due to demagnetizing effect of armature reaction.

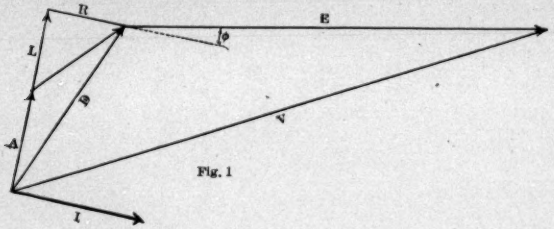


Fig. 1

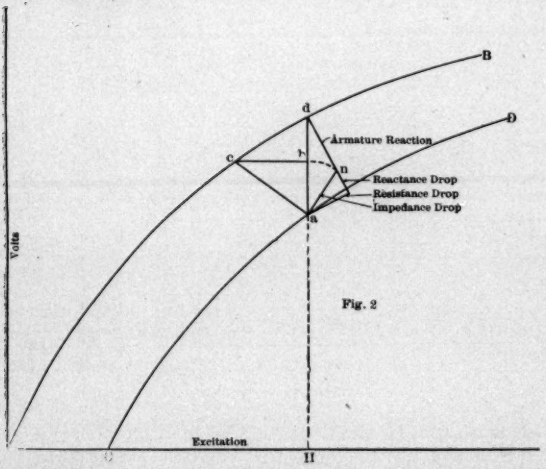


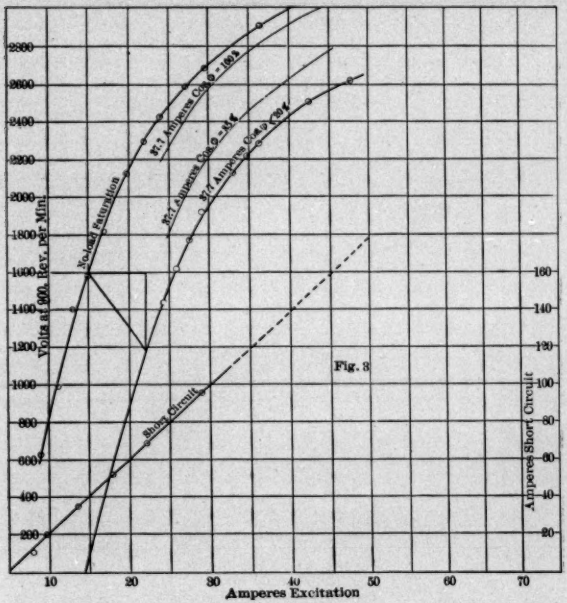
Fig. 2

I = current.

The armature reaction component A is represented in quadrature with the current since, like reactance, its effect is maximum when the power-factor is zero.

Let $A\ B$, Fig. 2, represent the saturation curve and $C\ D$ the regulation curve at zero power-factor. For any excitation

such as $A\ H$ the drop is $a\ d$ [1] and may be made the hypotenuse of a right triangle, as in Fig. 1, with the resistance drop as one leg, and the reactance drop plus armature reaction drop as the other. As the resistance is relatively small, no great error will result by swinging the impedance pressure n around to b and considering the distance $b\ d$ as armature reaction drop, instead of $n\ d$, $b\ c$ will then be the armature reaction expressed in ampere-turns, or exciting current, according to which we



plot as abcissas.[2] The total drop $a\ d$ may be designated as synchronous impedances. The distance $c\ b$ is constant for a given current, no matter what position along the curve it may

1. The diagram is not strictly correct since the drop $a\ d$ is represented in phase with $H\ d$. Fig. 1 shows that the total drop D can not be in phase with V, even at zero power-factor, unless the resistance is zero. However the resistance is small, so no appreciable error results.

2. "Experimental Basis for the Theory of Regulation Alternators," paper read by Mr. B. A. Behrend before the INSTITUTE May 19, 1903

have, so also is $a\,b$. However the distance $b\,d$ is not constant for a given current but depends upon the position on the curve (*i.e.*, is dependent upon the degree of saturation). Since $a\,b$ and $b\,c$ are constant, the hypotenuse $a\,c$ is also constant, and from this it follows that having the two, curves $A\,B$ and $C\,D$ given by experiment, if we can by trial find a line such that its direction and its length between the curves is constant, as we move it along the curves, we may construct a right triangle upon it, with legs parallel to the coördinate axes and equal respectively to armature ampere-turns and impedance drop.

It is also possible to calculate $c\,b$ from known current and number of conductors, from which $a\,b$ can be obtained by constructing the triangle. The following formula is found to give fairly accurate results.

$$A = 1/2\sqrt{2}\,a\,n\,I = 0.707\,a\,n\,I.$$

Where A is the demagnetizing effect of the armature turns per pair of poles a, the number of conductors per phase per pole, and n the number of phases.

Number of Machine.	Number of Phases.	Number of Poles.	Conductors per Phase per Pole.	Field Turns per Pair of Poles.	Armature Amperes.	Armature Reaction Expressed in Exciting Amperes = $\frac{0.707\,a\,n\,I}{\text{Field Turns}}$	Value of Armature Reaction Observed from Curves.
1	3	8	15	213	239	35.7	38
2	3	8	48	512	37.7	7.5	—
3	3	72	32	89	30	22.9	24
4	3	20	36	141	55	29.8	32
5	3	6	48	420	26	6.3	6.5
6	2	4	192	704	20.5	7.9	8.2
7	2	26	64	205	25	11	11
8	2	16	72	254	38	15	13.5

The accompanying table shows the values of A calculated for eight machines, also the values obtained by constructing a triangle. As the curves are plotted with exciting current as abscissas the expression for ampere-turns is divided by the number of field turns per pair of poles. In each case the proper triangle was found by trial. In most machines the hypotenuse of the triangle makes an angle of about 45 degrees with the coördinate axes. Figs. 3 and 4 are the curves for machines numbered 2 and 3. The saturation curves and curve for power-factor less than 20% have been ploted by results obtained when the machines were tested. The latter curve was obtained

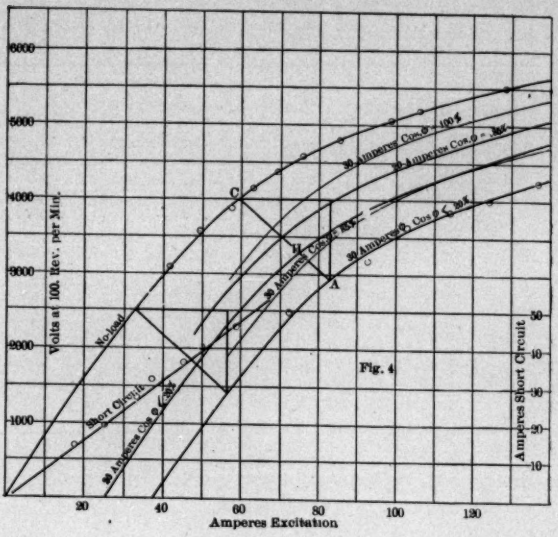

6000
5000
4000
3000
2000
1000
Volts at 100. Rev. per Min.
No load
Short Circuit
20 Amperes Cos φ = 100%
20 Amperes Cos φ = 80%
20 Amperes Cos φ = 30%
20 Amperes Cos φ = 0%
20 Amperes Cos φ < 30%
C
H
A
20
40
60
80
100
120
Amperes Excitation
50
40
30
20
10
Amperes Short Circuit

Fig. 4

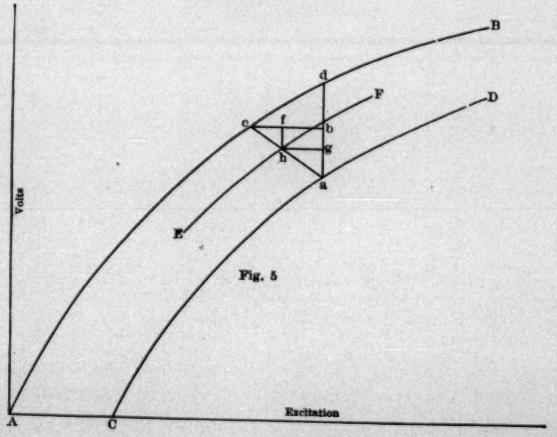

B
d
F
D
c
f
b
g
h
a
E
Volts
A
C
Excitation

Fig. 5

by loading the generator with an under-excited synchronous motor. It is impossible to obtain a strictly wattless load, but when the power-factor is below 20% the error in considering it as zero is very small.

Suppose we have the regulation curve for I amperes at zero power-factor, $C\ D$ Fig. 5, and wish to find the curve for some other value of current; for example I/x, at zero power-factor. Both armature reaction and impedance drop are now $1/x$ of their former value. Lay off $c\ f = c\ b/x$ and $b\ g = b\ a/x$. Construct triangle $c\ f\ h$. Now as the line $c\ a$ moves along the curve, the path traced by the point h will give the desired curve $E\ F$ for I/x amperes.

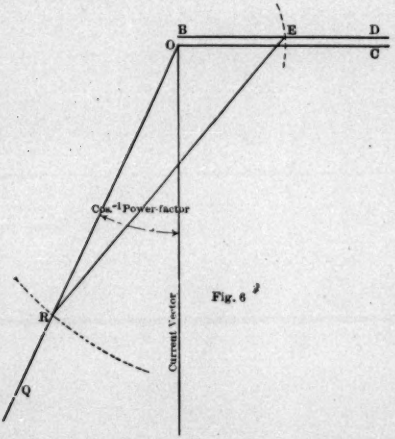


Fig. 6

As an illustration of the method, the regulation curve at zero power-factor for 20 amperes has been calculated for machine No. 3, see Fig. 4. The line $C\ A$ corresponds to 30 amperes, so for 20 amperes point H is located 2/3 of the way between C and A. The triangle is then moved and the point H describes the desired curve. The accuracy of this method for power-factors other than zero is somewhat questionable. The regulation curve for I/x amperes at zero power-factor should first be determined, and from this, if desired, the regulation at any other power-factor can be calculated by the following method.

Draw $B\ D$, Fig. 6, parallel to $O\ C$ a distance from it equal to the resistance drop. Lay off $O\ I$ the current axis, normal to

$O\,C$ and draw a line $O\,Q$ making with $O\,I$ an angle whose cosine is the power-factor for which we desire the regulation. For any excitation such as $A\,H$, Fig. 2, measure the drop $d\,a$, and using it as a radius strike an arc with O as a center, cutting $B\,D$ at E. Now with E as a center strike an arc equal to the no-load pressure $H\,d$, Fig. 2. This cuts $O\,Q$ at R. The length $O\,R$ is the terminal pressure for the excitation $A\,H$. This process is repeated for a number of points and a curve drawn through them. The work is greatly simplified if the same scale is adopted in Fig. 6 as that used in Fig. 2.

Having already obtained the regulation at zero power-factor and 20 amperes for machine No. 3, the regulation for 85% power-factor has been calculated by the method just described.

For a method of determining the regulation curve at zero power-factor, from the short-circuit curve, the reader is referred to Mr. Behrend's paper read before the INSTITUTE, May 19, 1903.

MEETING AT PITTSBURG, MAY 5, 1904.

DISCUSSION ON "CONTRIBUTION TO THEORY OF THE REGULATION OF ALTERNATORS."

V. KARAPETOFF:—The paper under discussion gives a complete method for the predetermination of characteristics of an alternator from its design. Three elements causing drop of pressure (beside ohmic drop) are taken into consideration: armature demagnetizing action, armature distorting ampere-turns, and armature self-induction. As these three causes are more or less independent of each other, they can be discussed separately.

1. *Armature Demagnetizing Ampere-Turns.*—The table given on page 298 of the paper by Messrs. Hobart and Punga gives in the first line demagnetizing ampere-turns for different ratios of pole-arc: pitch for a winding of one slot per pole. The numerical coefficients given there check very closely with the old formula:

$$\frac{0.57}{m} Sin \frac{\pi}{2} m$$

where m is the ratio of pole-arc to pitch, given by G. Kapp several years ago. The method of computation given in Appendix, page 320, shows that the same mathematical method was used as in Kapp's dynamos, with the only difference that Kapp directly integrated the expression for an instantaneous armature reaction, whereas Messrs. Hobart and Punga selected a long way of elementary mathematics. Their table for the "Breadth Factor." on page 299, given without explanation, checks very closely with Professor Arnold's factor,

$$Sin\left(\frac{\pi}{2}\frac{c}{a}\right),$$

where $\frac{c}{a}$ is the ratio of (coil breadth: pitch). As the table presupposes a distributed winding, the above factor must be integrated along one side of the coil, which gives

$$\frac{2a}{\pi(a-c)} Cos\left(\frac{\pi}{2}\frac{c}{a}\right)$$

and this last expression gives precisely the same results as the above table. If, however, the winding is distributed in but two or three slots per pole and phase, it seems more advisable to calculate directly the coefficient for each of the coils. The authors do not bring anything new into the method of determining armature demagnetizing action and use an already established and accepted theory.

2. *Armature Distorting Ampere-Turns.*—The authors make two assumptions to arrive at their results; namely, that at every instant the distorted flux acts as if it were concentrated in its center of gravity, and that the whole distortion corresponds to the average position of the center of gravity for an alternation. Once these assumptions are admitted, the results given in the second line of the table on page 298 are correct. But the assumption that a non-uniformly distributed flux can be concentrated in its center of gravity does not seem to be legitimate in this case. The authors begin with the distribution of the flux at a certain moment of time (Fig. 5 on page 297), and this is perfectly right. Now, if the distribution is known at any moment, the average distribution can only be found in a correct way by properly integrating the corresponding function, which expresses this distribution over a complete cycle, and not by making a new assumption. Once the problem is definite, every new assumption is superfluous, and therefore it can either be deduced from the data of the problem, in which case it is not necessary, or it contradicts these data and so leads to wrong results. If the authors would have followed the above-mentioned way, beginning with Fig. 5, they would have arrived at Guilbert's formula.

From a practical standpoint it is important to note that Guilbert's formula gives higher values for distorting ampere-turns than the method proposed in the paper under discussion.

3. *Armature Self-Induction.*—The authors do not establish any new data for the influence of self-induction, and they agree that with our present knowledge only a rough approximation in this respect is possible. They cite a formula for self-induction of open slots, based on calculation of the permeance of the paths for stray lines of force. For half-closed slots used in this country the corresponding formula is more complicated.

For free length of the coil they assume from 0.4 to 0.8 lines of force per centimeter of length. This is based on the following method:

Free ends of coils are supposed to have a semicircular shape; Professor Perry has given an approximate formula for self-induction of a flat circular coil without iron. The authors apply this formula to their case, forgetting that self-induction of a semicircle is by no means equal to half the self-induction of a complete circle. Besides, the proximity of the iron completely changes the conditions under which the formula has been deduced; moreover, usually the ends of the coils are not semicircular, and we do not know how far a change in shape affects the self-induction. Thus, the above data, 0.4 to 0.8 lines of force, seem to have no sufficient justification. The question of mutual induction of the phases is not mentioned at all in the paper under discussion.

Concerning an experimental verification of their method, the authors give results of short-circuit tests on 18 different

alternators, most of which check very well with their formulas. But it must be borne in mind that on short circuit the current is lagging almost 90° behind the e.m.f., so that there is no armature distorting action, only demagnetizing ampere-turns, for which the authors use the commonly-established, generally-accepted theory, which thus seems to get a new verification. As armature self-induction has only subordinate action in well-designed modern machines, the above results can hardly be considered as sufficient for accepting the method of calculation of self-induction proposed by the authors. This is the more true, as they do not take into account the mutual induction of the phases, which according to the data recently published by Professor Niethammer, in certain cases can almost double the effect of self-induction.

Of course, the authors give in their paper a complete verification of their method of calculation on a machine, including tests of high power-factors, where distorting action comes more into prominence; but on the other hand, Mr. Guilbert also verified his formula on a number of alternators which had been tested at the last Paris Exposition; so that so far the question remains undecided.

Messrs. Hobart and Punga certainly deserve our grateful acknowledgments for publishing a complete method with numerical applications. They bring it forth in a popular form, and every simplification of theory which makes it easier for practical application promotes a better design; at the same time it gives more opportunity for verification of the theory itself and separates its sound principles from mere hypothetical assumptions.

Discussion on "Contribution to the Theory of the Regulation of Alternators."

H. M. Hobart and Franklin Punga (*by letter*): The authors agree with Mr. C. A. Adams, Jr., that their theory is suitable primarily for the designing engineer, and starting from this basis, all the factors involved in the armature reaction have been calculated. But to make this theory applicable as a check on specified regulation it is not necessary to invent an altogether new and different theory, as all the factors examined in the one case also exert their influence in the other case. It is, however, very desirable that further experimental investigations should be made bearing on the nature and magnitude of those components the predetermination of which is still inexact. These components are:

The self-induction of the armature itself;

The leakage-factor of the field-spools;

The saturation curve.

The self-induction of the armature itself may be experimentally determined in two ways, and the possibilities of having two different methods for its determination should give a much desired additional check. The one way is to measure the self-induction of the winding, and at the same time, by means of an exploring coil, the component crossing the air-gap; the difference between the two fluxes thus determined would give the stray flux in the slots and associated with the free length of the winding. A second way of measuring the pure self-induction is by means of the short-circuit curve, which contains the effect of self-induction and of demagnetizing reaction. As the demagnetizing ampere-turns can be calculated fairly accurately—even for air-gaps not at all uniform—this would allow of a determination of the remaining part, *i.e.*, of the pure self-induction.

The measurement of the leakage-factor and the plotting of the saturation curve involve nothing new. The measurement of the armature reaction at full load and zero power-factor would serve as a further check on the exactness of the calculation.

It is quite true, as Mr. Behrend points out, that the shape of the saturation curve may—besides the ohmic drop and the ratio pole-arc to pole-pitch—change the relation between regulation at unity power-factor and at zero power-factor. A machine with large air-gap and low field saturation may have the same regulation at zero power-factor as another machine with small air-gap and high field saturation, but the regulation at unity power-factor will most probably be considerably better in the first machine; or if the regulation at unity power-factor is the same for both machines—ohmic drop and ratio of pole-arc to pole-pitch and all other important factors being the same—the machine with the greatest part of its field ampere-turns required for the saturation of the iron will have

the lowest regulation at zero power-factor. Such extremes as 5% on purely inductive load and 10% on non-inductive load, as mentioned by Behrend, are impossible, unless the ohmic drop is from 5% to 10%. This point possesses considerable interest as regards the design of alternators, but not as regards the reliability or unreliability of the method under consideration.

We find the statements of Mr. W. L. Waters to be somewhat confusing and are obliged to differ with him with respect to most of his criticisms. From his "theoretical conclusions" Mr. Waters maintains that the lines which cross the air-gap should also be considered as belonging to the pure self-induction, but his practical experience leads him to think that such a step would show a wide discrepancy between observed and calculated points; and so it would. Hence the fault must lie in Mr. Waters' theoretical conclusions.

The authors were not aware of Mr. Adams' publication in the *Harvard Engineering Journal* (Nov., 1903), but they have never intended to claim any priority for this method of calculating the influence of the leakage, as Rothert and many

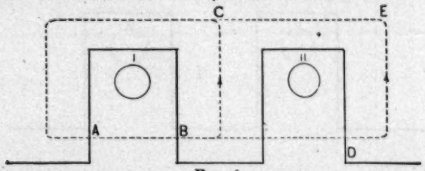


FIG. 1.

others had already employed it, and the authors considered it as an already well-known method. To whom the priority in this case belongs the authors are not prepared to state. A complete investigation of the priority in such a case is a very considerable undertaking. It possesses but little interest to most engineers and might with advantage rather be left to books than to papers, though, on the other hand, acknowledgement of priority should preferably be made when readily practicable and not involving an exhaustive historical research. It is, however, surely beyond the scope of a paper dealing with a problem in practical engineering, to carry this matter so far as Mr. V. Karapetoff would require, in acknowledging the "breadth-factor" to Professor Arnold as the term has long been a familiar one in the sense employed by us.

Mr. Karapetoff has confined his criticism to stating that each component of the complete theory has already been used by other authors. Even if this were the case the usefulness of the theory as a whole is in nowise less; the authors are nevertheless of the opinion that there are a few points which have

been neglected in all previous theories relating to this subject. These, of course, would be the essential parts, so far as priority is concerned, but they need by no means be the most important parts of the theory as a useful whole. The chief point is that the armature stray lines crossing the air-gap cannot be defined as pure self-induction, that they therefore cannot be treated like an ordinary vector, that they only increase the angle of lag between mid-pole position and centre of armature ampere-turns, and that they have no effect on the internal pressure.

Mr. Karapetoff asserts that no account has been taken of the mutual induction of the coils. This is another essential point in which we claim priority, for the mutual induction has been taken into account in our method. Thus all those lines crossing the air-gap and defined by many authors as belonging to the self-induction, are produced by the sum of all the armature conductors. It is exactly this mutual induction which causes the stray flux (Path II), to have a nearly constant position with reference to the main flux in polyphase generators.

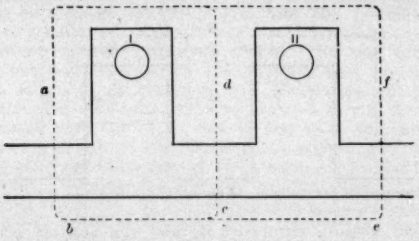


FIG. 2.

For the pure self-induction (Path I), the mutual induction has been neglected, as it is very easy to see that it can never amount to more than 5% or 10% of the total pure self-induction, and as this latter is only a small component of the total armature reaction, it is evident that taking into account this mutual induction would be an absurd refinement.

Conductor I carries current, while its mutual inductance toward conductor II has to be determined. It is clear that the stray flux has to follow the path *A B C* (Fig. 1), thus constituting self-induction, or the path *A B D E*, thus constituting mutual induction with respect to conductor II.

The amount of the flux following these two paths will be inversely proportional to the resistance along *B C* or *B D*, and as in the one case, the flux has to pass along through the tooth, in the other case, through a large air gap—width of slot—the flux following the path *B D* will be far smaller in

amount than the flux following the path $B\,C$. As in modern generators there are seldom less than two or three slots per pole per phase, the percentage of the mutual self-induction will be at least two or three times smaller than in the above case, so that it can easily be understood that the mutual induction component of the pure self-induction is only a few per cent.—say 1% to 5%—of the pure self-induction.

Quite different is the case with the lines emerging from the armature and crossing the air-gap (Path II). The lines following path $a\,b\,c\,d$ (Fig. 2) have approximately the same resistance in the magnetic circuit as the lines following path $a\,b\,e\,f$ and constituting the mutual induction.

This is one of the reasons leading the authors to split the armature stray flux into three classes; and the mutual induction in Path II has been regarded as an important factor which has been taken into account in no other theory.

It would thus appear that Mr. Karapetoff's criticism has chiefly related to deploring the absence of the very factor which is for the first time provided for in the authors' method.

BLANK
PAGE

A paper presented at a Meeting of the Seattle Branch of the American Institute of Electrical Engineers, Seattle, Wash., April 14, 1904.

Copyright 1904, by A. I. E. E.

OPERATION OF SYNCHRONOUS CONVERTERS.

BY S. C. LINDSAY.

It is the purpose of this paper to give a history of the experience we have had with 60-cycle synchronous converters in Seattle during the last three years and a half. As the Seattle Electric Company has a greater capacity in 60-cycle synchronous converters in daily operation than any other company in the United States, and as they have been operated under a variety of conditions, the writer thinks that his experiences might be of interest to others who are operating the same class of apparatus.

In the summer of 1900 we put into service two 550-volt compound-wound synchronous converters which were supplied with alternating current from the Snoqualmie Falls Power Company, the direct current from these synchronous converters being used to operate street cars and stationary motors. At that time the Snoqualmie Company was transmitting to Seattle at 15 000 volts over two- to three-phase lines, the conductors for each line being No. 2 solid aluminum wire. It was originally planned to use one line for power and the other line for lighting and such power loads as were not subject to large and sudden changes. The current for the synchronous converters was transformed to 340 volts by three 500-kw. transformers connected in $\triangle$ on both sides.

With 15 000 volts on the lines and the lines in multiple, one synchronous converter would operate satisfactorily up to full load; when the second synchronous converter was put in they would begin to pump immediately, although the load would not be increased beyond the capacity of one synchronous converter. If both machines were left in circuit the pumping

would soon become so violent that the transmission line circuit-breakers at the power-house would open. Various adjustments of the field strengths between maximum and minimum improved matters very little. It was tried a number of times to operate two machines under this condition, but without success. At times there would be several hundred horse power of induction motors in Seattle operating from the same system. We tried to operate the synchronous converters both with and without the induction motors in service, but without success, the results being a little more favorable with the induction motors running.

When the transmission lines were separated in Seattle, but still supplied from the same bus-bar at the power-house, we tried to operate a synchronous converter from one line and the induction-motor load and lights from the other line; with a very weak field a single synchronous converter would run comparatively steady without load, but would pump violently when loaded to one third of its rated capacity, especially if it were a street-railway load. With the lines divided as above two synchronous converters were synchronized on the same transmission line, but were not loaded nor even paralleled on the direct-current side. After running under this condition for a few minutes they began to pump, and the pumping soon became so violent that they had to be shut down.

After these results, no further attempts were made to operate two machines at a time until the power company began to transmit at 30 000 volts, when it was found that both synchronous converters would operate entirely satisfactorily up to their full capacity with the transmission lines in parallel; and when the lines were separated one synchronous converter would operate perfectly up to full load and 50% of overload, but when the second machine would be switched in pumping would commence unless the load was reduced. We could carry more load without any disturbance on one machine than we could on the two. It must be borne in mind that when these attempts were made to operate two synchronous converters from one line the line was loaded in almost every case with the induction motor and lighting load that was always carried when both lines were in parallel.

In the spring of 1901, a third 550-volt synchronous converter was installed in the same sub-station with the other two machines, and connected to the same bank of step-down trans-

formers. When the three synchronous converters were running at the same time they were, of course, in parallel on both their alternating-current and direct-current sides.

A 250-volt shunt-wound 500-kw. two-phase synchronous converter was also installed at the same time in another sub-station about one-quarter of a mile from the station where the 500-volt synchronous converters were installed, and was operated from the same system.

The addition of these last synchronous converters caused no trouble whatever as long as both transmission lines were in parallel, but when it became necessary to place the entire Seattle load on one line it was found that the 250-volt synchronous converter and one 550-volt synchronous converter would operate satisfactorily, but that two 550-volt synchronous converters would not operate satisfactorily when the 250-volt synchronous converter was shut down.

When the transmission lines were multipled at Renton, and one line cut out between Seattle and Renton, all of the load in Seattle being carried by a single line between these two points and the two lines between Renton and the power-house, all of the 550-volt synchronous converters and the 250-volt synchronous converter could be operated at the same time; but when all of them were heavily loaded there was more or less pumping, but it was not serious enough to interfere with the lighting to any great extent. Within the last year the conductors in the transmission lines have been changed from No. 2 aluminum to 0000 aluminum between Renton and the power-house, and to 00 aluminum between Renton and Seattle. Since this change two or more 550-volt synchronous converters can be run from a single line without any trouble. The trouble experienced when first trying to operate more than one synchronous converter from a single line must have been due to excessive line drop which caused an interchange of current between the synchronous converters.

While operating the three 550-volt synchronous converters from the same bank of transformers it was necessary to use great care in adjusting their field rheostats so as to keep the load equally divided among the synchronous converters. If one synchronous converter was given a weak field and the other two a strong field, pumping would commence and soon become serious if the proper adjustment were not made. We had all three synchronous converters thrown out of synchronism several times

from improper adjustment of their field currents. While operating under this condition it was found that a dirty commutator or too much oil applied to a commutator for the purpose of lubrication would cause serious trouble, and on one or two occasions threw all machines out of synchronism. Shifting the brushes to find the neutral point was also a prolific source of trouble. After these causes of trouble had been discovered we got fairly good results, but only by the most careful attention to the machines.

Experience with these rotaries operating from one bank of transformers leads the writer to believe that a worse combination cannot be had, and is something that should never be done except as a makeshift.

After running under this condition for two months a separate bank of transformers was installed for each synchronous converter, each bank consisting of two 300-kw. transformers, transforming from 2200 to 340 volts, these transformers in turn being connected to a single bank, transforming from 30 000 to 2200 volts, both transformations being made on the Scott two-phase to three-phase system. This change in no way affected the results of an attempt to operate on a single transmission line, but the troubles experienced from operating the three synchronous converters from a single bank of transformers were entirely removed.

The one thing that has caused more trouble than any other in the operation of synchronous converters, and the thing that has been responsible directly and indirectly for over 90% of all the troubles we have had with them, has been the frequent breaking down of the transmission line. Almost every time the line would break, all of the 550-volt synchronous converters then running would flash-over at the commutator, making a loud report very similar to the discharge of a cannon. The breaking of the line caused a rise of pressure at the commutator of the synchronous converters great enough to jump the space between the positive and negative brush-holders of the machines. There were only two or three cases when the line broke down that the flashing-over did not occur. On several occasions when the line broke armature coils were burned out simultaneously with the flash. The flashing did considerable damage each time it occurred, by burning the commutator and brush-holders and tearing away parts of the mica insulation between the copper segments, which left small pockets that soon filled up with particles of copper and carbon dust. Whether the rise of pressure

at the commutators was caused by the sudden opening of the line or by a short circuit between the broken wires and the other two line wires is a matter that has never been determined, as no one qualified to make an intelligent report was ever present at the point of trouble when a break occurred. This trouble was finally stopped by grounding the neutral point of the two-phase windings of the step-down transformers. Although this was done primarily for another purpose it produced an effect on the synchronous converters that we had long desired.

If the commutators are in first-class condition the damage done by a single flash has never been sufficient to cause serious trouble unless armature coils were burned out; the damage to the commutator being quickly removed by the use of a file and coarse sandpaper. When line troubles were quite frequent, say three or four times a week, the damage done to the mica segments by one flash would not be removed before another flash would occur, and the result was that a number of mica segments in each commutator would be wasted away from 1/32 to 1/16 an inch below the surface of the copper segment. These places would soon fill up with particles of carbon and copper dust, causing short circuits between segments. These short circuits would burn out, causing a flash and explosion at the commutators very similar to that caused by line troubles, the principal difference being that current did not disappear from the transmission line when trouble was caused by these short circuits. We experienced a great deal of difficulty from these short circuits before the cause of the trouble was determined. The difficulty in locating the trouble was due to the fact that when a flash-over would occur and throw the synchronous converter out of synchronism they could be immediately brought to voltage, synchronized, and loaded again without giving any evidence of the cause of the trouble. Sometimes the synchronous converters would be thrown out a number of times in a day from this cause, and again they would run for one or two days without any trouble. The cause of the trouble being determined, it was easily remedied by turning the commutators down until the mica and copper segments were even.

In the summer and fall of 1902 all of our synchronous converters were moved to the Post Street station, which had just been completed, and we now have in this station nine 500-kw. synchronous converters, five of which are 550-volt, three-phase, the other four being 250-volt, two-phase, which are used on the

three-wire lighting system. As stated previously, each synchronous converter is connected to its own bank of transformers, the transformers for the 500-volt synchronous converters being connected on the Scott system transforming from two-phase to three-phase.

The power purchased from the Snoqualmie Falls Power Co. is also delivered to this station, making it a combined generating and sub-station. The synchronous converters operate equally well from the steam-driven generators in this station without the use of special inductance coils as they do from the transmission lines, the only exception to this rule being when the steam-driven generators were operating considerably below their normal speed, say 114 rev. per min., their normal speed being 120 rev. per min. The action of the synchronous converters when run from the steam-driven generators at this reduced speed seems to be a tendency to slow down every time the engines pass their centers, which produces a very noticeable effect on all incandescent lights supplied from the generators and lighting synchronous converters. This trouble is caused by the irregular angular velocity of the prime movers and cannot be considered as synchronous converter trouble. In no case has this caused any trouble other than the effect on the incandescent lamps, even when the speed of the generators would fall as low as 110 and 112 rev. per min. As stated before, this effect entirely disappears when the generators are running at their normal speed.

During the last 18 months the transmission line troubles have been very much less than they were before, and the troubles with the synchronous converters have practically disappeared. As the grounding of the neutral point of the secondary winding of the step-down transformers prevents the synchronous converters from flashing-over at the commutators when line trouble does occur, and various other improvements have been made in the transmission line, we have not had any more trouble with these synchronous converters than would be had with an equal number of direct-current generators of the same capacity.

Having the two sources of supply in the same station, where all of the synchronous converters are located, it has been necessary to operate some of the synchronous converters from the steam-driven generators and some of them from the power supplied by the Snoqualmie Falls Power Co., all synchronous converters being operated in parallel on the direct-current side. This combination is used with both types of synchronous con-

verter, the pressure of each synchronous converter being controlled by Hartford regulators. This arrangement serves to steady the pressure variations caused by the fluctuations of the street-railway load; and the results are very much more satisfactory for smoothing out the load, than when all synchronous converters are operated from the same source of supply.

As for care and attention necessary for synchronous converters, it is substantially the same as that required by direct-current generators of the same pressure and capacity. The commutators require sandpapering about once a week. Occasionally a commutator will require sandpapering twice in one week. No. 2½ sandpaper is used to bring the commutator to a smooth surface, and it is then finished with No. 1 sandpaper. A small amount of oil is used on each sheet of sandpaper to prevent the dust from flying. It is very bad practice to saturate sandpaper with oil for use on a commutator, as the excess of oil will form a paste with the copper dust that will be forced into the mica, if the mica is as soft as commutator mica should be. The excessive use of oil is especially bad if there happens to be a number of mica segments in a commutator that are not uniformly even with the copper segments. Very good results are obtained by spreading the oil evenly over the sandpaper, then absorbing the greater portion of it with clean waste, leaving enough to prevent the copper dust from flying, but not enough to form a paste.

We have tried for a long time to get a carbon brush that would be satisfactory, and we think that we have found one. In the meantime we have found a great many that were not satisfactory, the average life of a set of carbon brushes being from three to six months. We have a set of brushes in a synchronous converter that were put in the 28th of last May, and they are about half worn out. The wear on this commutator has been very small also. We have a set of brushes in another machine that has been in use since February 23, and the wear on these brushes was found to be about 3/16 of an inch when measured to-day. The brush just mentioned is a medium-soft brush with a good deal of graphite in it. Pure graphite brushes are not at all satisfactory for synchronous converters.

BLANK
PAGE

A paper presented at the 177th meeting of the American Institute of Electrical Engineers, New York, May 17-18, 1904.

Copyright 1904, by A. I. E. E.

NOTES ON FLY-WHEELS.

BY H. H. BARNES, JR.

The choice of a fly-wheel for reciprocating engines direct connected to alternators is a somewhat serious matter in view of synchronous operation. With prime movers giving a uniform torque, and for belted units, a fly-wheel for the general purpose of obtaining a proper mechanical balance for the operation of the engine is all that is required, and the fact that an alternator has to be driven does not enter into the problem. With direct-connected reciprocating engines, however, it is customary to specify a fly-wheel that will limit the angular displacement from the mean position under the worst conditions to a given number of degrees, the limit usually being set at $\pm$ 2.5 electrical degrees. This rule, it has been claimed, gives the best all-round results for the operation of alternating-current machinery. In the following pages an outline has been given of comparative tests of alternators with both light and heavy fly-wheels, the results of which go to show that a good word may also be said for somewhat lighter wheels than the ones to which the above rule leads.

Anyone who has watched the generator instruments in a plant operating alternators in multiple will have noticed a slight periodic swing of the pointers. A closer study of these beats shows there are two distinct varieties. Usually the swing is in step with the revolutions of the engine and is entirely independent of the field excitation of the alternator. In other cases the beats have a distinct period of their own that varies with the field excitation and consequently with the bus-bar pressure. In the first case the variation in the driving torque of the engine, which repeats itself periodically with each revolution, imposes itself upon the alternators and gives forced oscillations. The

variable period, on the other hand, is that of natural oscillation. Natural oscillations invariably appear when an alternator is paralleled a little out of step, and under some other conditions as well, and occasionally even predominate to the exclusion of forced oscillations. At all events, it is an easy matter to determine the natural period experimentally. Its importance and its intimate relation to fly-wheel capacity will be more thoroughly appreciated if we analyze the results obtained in three different plants in which alternators of identical design are direct connected to cross-compound reciprocating engines. The interesting feature in these plants and the reason for singling them out being that, while the generators are identical and the engines nearly so, the fly-wheels differ very considerably in weight.

The generators throughout are 500-kw., two-phase, 100 rev. per min., 60-cycle units of the inductor type. Their short-circuit ratio with no-load excitation is 3.5.

The following table gives the fly-wheel data:

	Fly-Wheel.		Moment of Inertia in lbs. x (ft.)^2		
Plant.	Weight of rim in lb.	Outside diameter in feet.	Fly-wheel.	Revolving element of alternator.	Total.
A	30 000	15	46 150	16 900	63 050
B	50 000	16	92 430	16 900	109 330
C	60 000	18	143 500	16 900	160 400

The natural frequencies obtained experimentally for each plant at no load are shown in Fig. 1 on next page.

It will be noted that the units with the lighter wheels have the higher natural frequency, as was to be expected. The effect of this difference in natural frequency upon the behavior of the engine-governors is marked. With the governor dash-pots in the condition in which the engine builders left them, parallel operation at normal pressure was a failure in all three plants. Upon throwing two units together, cross-currents would build up, and eventually the surging would become so violent that the machines would have to be separated. The frequency of surging was that of natural oscillation throughout. With the same setting of the engine dash-pots, however, the machines in *C* would run together acceptably at no load at pressures of 60% and less of normal, and the machines in *B* at pressures of 40% and

less of normal, whereas those in A failed to operate satisfactorily at 50% of normal, which was the lowest pressure tried.

By artificially decreasing the oscillations of the governors, by means of the dash-pots, the units in A could be made to operate well at normal and higher pressures. The units in B showed an improvement at pressures considerably above normal (tests at reduced pressures had to be omitted here to avoid interfering with the commercial operation of the plant), while no improvement whatever was noticeable in C, except for the lower pressures. The former average limit of 60% of normal being extended to over 80%.

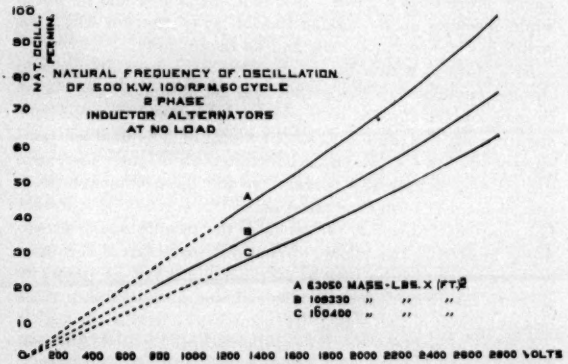


Fig 1.

A still further increase in the damping of the governors in C, however, resulted in a decrease in the limiting pressure, until with completely-blocked governors parallel operation became impossible at any and all pressures. This result and similar ones obtained elsewhere would indicate, it seems, the existence of an inherent tendency toward cumulative surging that is in no way connected with the behavior of the engine governors.

The origin and nature of this tendency are not directly apparent. It seems likely that they are intimately connected with the armature reaction of the alternators, but whether a departure from a uniform turning moment in the prime mover is also essential to its appearance may be doubted. As far as the writer is aware, there is no indication in dynamics in the

theory of forced and natural oscillations of a possibility of forced oscillations producing cumulative surging. If this is so, it might be imagined, although there is no direct experimental evidence to support the idea, that the surging which so frequently appears and is at times so hard to control, in alternators operating in multiple (to limit ourselves to a definite case) is due, not to the lack of uniformity in the turning moment, but rather to the effect of heavy wheels upon armature reaction phenomena. It is also probable that we have operating, in addition to this, causes of the same nature as those that produce cumulative surging in a Watt governor system. It should be clearly understood that this is hardly more than a guess. But it is one that would be worth while checking up by making the following test. for which the writer has unfortunately not had an opportunity.

In a plant in which direct-connected alternators are given to chronic cumulative surging that will not disappear even when running on the throttle with governors blocked, disconnect the engines and drive the alternators by means of individual constant-current motors. If we parallel the alternators under these conditions and surging still persists, we will have eliminated from the problem the angular variation of the engine. If it should fail to appear, however, the origin of the trouble would be definitely located in the engine. Whatever the origin of this inherent tendency to surge may be we must more than counteract its effect to insure successful parallel running, a result that may be brought about in two ways: by using heavy wheels—or else by operating at reduced pressures—the natural period of the unit may be lengthened to such an extent that the engine governor, instead of adding to the disturbance will have time to grapple with any surging that may appear, and wipe it out. An example of this is the behavior of the machines in plants *B* and *C* at reduced pressures. This solution has the drawback of leading to wheels of prohibitive weight for slow-speed units, and furthermore, of making the successful operation of the plant dependent to a certain extent upon the adjustment of the engine governors.

The second and better way to overcome the inherent tendency to surge is to provide sufficient electrical damping. Any oscillations that may appear will then be taken care of by the damping, and the assistance of the governor will no longer be required. In fact the damping action will be more rapid and final if the governor dash-pot is adjusted so that the governor will not respond to natural oscillations, as, in the majority of cases, it

would only strive to maintain the latter if left free to act. As it is easier to adjust the dash-pot with this end in view, to bridge over a short period than a long one, we see that light wheels with their short periods are more desirable in this respect than heavy ones. This argument may seem weak at first when applied to plants in which forced oscillations predominate, but experience teaches that the disturbing influence of the natural period is felt, even when there is no immediate indication of its existence on any of the switchboard instruments. More delicate instruments than the ones usually used would probably reveal the natural period, and even with instruments which appear at first to indicate forced oscillations only, a battle for supremacy between the forced and natural periods may frequently be detected by scrutinizing the movements of the pointers with more than usual care.

To bring out a little more clearly the effect of a change in weight of wheel upon the behavior of the engine governor, we might say that with very heavy wheels and consequently long natural periods the governor is able to kill off unaided any surging that may attempt to develop. With very light wheels, on the other hand, the governor is barely affected by surging and the task of holding it down devolves upon the electrical damping of the units. There is an intermediate zone between these two extremes in which the governor would directly assist the tendency to surge if it were not prevented from doing so by special adjustment of its dash-pot. If such adjustment is not made, it is evident that what electrical damping there is will be more sorely taxed, and the heavier the wheel the more likely it will be that the damping will be unequal to the task of carrying this additional burden and that cumulative surging will set in.

If neither of the conditions we have been discussing is met, as in plants *B* and *C* at normal voltage, successful running may be said to be out of the question. The best remedy for the cumulative surging that will undoubtedly set in in such cases is to increase the electrical damping of the machines, until it is able to hold in check the inherent tendency to surge. This was done in the above plants with eminently satisfactory results.

It may also be pointed out that the successful running at normal pressure with dampened governors in plant *A*, compared with the failure to run in plants *B* and *C*, would indicate that the relative increase in electrical damping is more rapid than the corresponding increase in the inherent tendency to surge for a given decrease in weight of fly-wheel. Should this be corroborated

by similar observations elsewhere, a further most weighty argument would be added in favor of light wheels. However this may be, the tests already described, and they are but a few of those that could be cited, lead to the conclusion that a decrease in fly-wheel capacity is not synonymous with an increased tendency to surge on the part of alternators. The following observations will emphasize this point still further.

In plants *A* and *B* individual exciters are belt driven from the shaft of each alternator, and facilities for paralleling the exciters are provided, besides the usual switches. With this arrangement, if two alternators are paralleled while energized by their own separate exciters, and the pressure and dash-pot conditions are such that cumulative surging sets in, the surging may be very rapidly stopped at all loads by simply paralleling the exciters. Tests were made to ascertain the nature of this action of the exciters. The results proved that it is directly comparable to that of electrical or viscous damping and not related to the constancy of the exciter pressure.

Other conditions being the same, it is reasonable to assume that the time taken to dampen out cross-currents by paralleling the exciters would give a fair indication of the relative tendency to surge existing in these two plants. Actually, the average time required is about the same in both plants, with possibly a slightly quicker action in *A*. From which the conclusion must again be drawn that a decrease in fly-wheel capacity and consequent increase in angular variation while running does not decrease the stability of the generators. In making these tests it was noticed that individual results in *A* were affected to a very slight extent by the relative position of the driving cranks of the engines. In *B* and *C* and numerous other plants experimented upon, this influence, if it existed at all, was so slight that it was impossible to distinguish it from that due to other causes.

Passing on to another phase of the subject, we find that the limitation usually imposed upon the maximum angular variation of alternators is intended, among other things, to limit the cross-currents due to this variation. Thus, for a variation of $\pm$ 2.5 electrical degrees and a short-circuit ratio of 2.5, the cross-current will amount to approximately 10% of the full-load armature current, and no more. If we consider, however, that a 10% current results in an $I^2 R$ loss of less than 1% of normal, and that the normal $I^2 R$ armature loss is itself but a fraction of the total loss in the generator, we realize that at least a 25% cross-

current may be permitted without fear of appreciably increasing the total losses. Especially as such cross-currents would appear under the most unfavorable conditions of load and cut-off only, the average exchange of current during the day's run undoubtedly remaining well below the maximum. It might be well to add that there should be not any trouble from blinking of the lights if the cross currents do not exceed the value mentioned. There do not appear to be any very good reasons, therefore, why objections should be raised on this score to the use of lighter fly-wheels giving a considerably great variation than the customary 2.5 degrees.

We shall now examine the effect of a light wheel on the generating units upon the behavior of synchronous apparatus. We have in *C* a good example of a plant working under these conditions. Exceptionally light wheels are in use there and numerous synchronous motors and rotaries are in operation on the system. Not a trace of trouble has developed in this plant since the start, however, notwithstanding the light wheels.

Some interesting experiments that are very much to the point were made recently by Mr. P. C. Oscanyan. In a plant equipped with 850-kw., 60-cycle, 90 rev. per min. alternators, direct connected to cross-compound reciprocating engines, the fly-wheels were designed to maintain the angular variation within $\pm$ 2 degrees of mean. The rims of the wheels were laminated and weighed normally 100 000 lbs. With a machine with less than one-quarter of its rim in place running singly and in parallel with a completed unit, no difference whatever could be detected between the behavior of the incomplete machine and that of its neighbors. It would operate in parallel under all conditions of load, and when running singly would carry a load of synchronous converters without any indication of trouble. On the strength of this, and without going further, it may be said that surging and allied troubles in synchronous apparatus are not necessarily associated with light wheels and increased angular displacement. They are due, it would appear, more to certain imperfectly understood relations between the number of generating and receiving units, their moments of inertia, output, speed, etc., than to the existence of a more or less pronounced angular variation dependent upon the fly-wheels.

The question of electromechanical resonance remains as being about the only possible further source of trouble that might be introduced by a change in weight of wheel. Resonance, it may

be added by way of explanation, is said to exist in a system when the ratio of forced and natural frequencies is nearly or exactly equal to unity; its effect is a tremendous amplification of the original forced oscillation.

By referring to the curves of natural frequencies on page 355, we see that the normal natural frequency of the units in plant *A* is 81 per minute. The forced frequency determined by the revolutions is 100. By forcing the excitation until we reach pressures and consequently natural frequencies, that are considerably above normal, we might expect to see the effects of approaching resonance. In reality, noticeable cross-currents begin to appear at a frequency of 87; at 90 they are already quite pronounced. They are not cumulative, however (provided the engine dash-pots are in order), but increase and decrease periodically with a main frequency equal to the difference between the forced and natural frequencies. The slip, as it were, between the two frequencies may be counted in this way with great precision. We have here the phenomenon of interference, which appears whenever the damping of a system is very weak. If we increase the damping in this case, as, for instance, by paralleling the exciters, the main period disappears, and the cross-currents take on an average value with a regular but slight beat of forced frequency. A further increase in natural frequency runs up the cross-currents very rapidly until they are far in excess of the full-load armature current for a ratio of frequencies nearly equal to unity. These results show clearly enough that resonance is a real and very serious danger, and one to be avoided with the utmost care, as there is no acceptable way of overcoming it when encountered in practice. In order to avoid it, we should have a formula for predetermining the fly-wheel and the corresponding natural period, which we could then make as different as we choose from the forced period, already determined by the revolutions of the engine.

The oldest and at the same time the best formula for this purpose that the writer knows of, was published by Paul Boucherot in 1892, in Vol. 45, issue No. 31 and 32 of *La Lumiere Electrique*. It is, with a recent slight modification:

$$T = 0.31\, N \sqrt{\frac{M}{f \times E \times I_e \times p}}$$

where

T = Natural period of oscillation in seconds at no load.

N = Revolutions per minute.

M = Total moment of inertia of all rotating parts (fly-wheel, crank discs, inductor or revolving field, etc), expressed in lb. $\times$ (ft.)^2.

f = Electrical frequency per second.

E = Effective e.m.f. per phase or leg.

I_e = Effective short-circuit armature current corresponding to E.

p = Number of phases.

The greatest discrepancy that has thus far appeared in checking this formula experimentally in nearly a dozen plants is one of + 6%, the calculated period being that much longer than the observed one. The mean error for all the plants was + 3%. The reliability of the formula for practical purposes is therefore beyond doubt.

With this formula to assist us, it is an easy matter to predetermine a fly-wheel that will at least avoid resonance once we have agreed upon the closest ratio permissible between the forced and natural frequencies. The choice of this ratio depends upon numerous considerations. In the first place we have, as the essence of resonance, the increase in angular variation that is bound to appear after paralleling, even when absolute resonance is still quite remote. There is also the possible error between the calculated and the actual fly-wheel, the rather doubtful values that are sometimes used for the short-circuit current and the increase in natural frequency with the load and with a decreasing power-factor. Making due allowance for these various factors, let us assume for the moment a natural frequency at no load equal to 70% of the forced.

If we introduce this condition into the formula on the preceding page, and substitute $P \times k$ for $E \times I_e \times p$, and $W r^2$ for M wherein P is the normal output of the alternator in kilowatts, k, the ratio between the short circuit and full-load armature current, W the weight in lb. and r the radius of gyration in feet of all the revolving parts combined, we get

$$W r^2 = 25 \frac{P \times f \times k}{\left(\frac{N}{100}\right)^4}$$

It remains to be seen if a wheel based on this formula is sufficiently heavy to keep the cross-currents within bounds. It appears upon examination that for such a wheel the maximum cross-current between alternators driven by any average cross-

compound steam-engine would not exceed 25% of the full-load armature current, even under the worst conditions, which may be considered an entirely permissible figure.

For an ordinary cross-compound unit and a short-circuit ratio of $k = 2.5$, the maximum angular variation may be assumed to be within $\pm$ three electrical degrees of mean when running singly. With a 70% ratio of frequencies, however, the angular variation of a unit running singly may be practically doubled upon paralleling it in with its fellows, and it is upon this increased variation that the calculation of the cross-currents has been based. With alternators with a higher short-circuit ratio and therefore better regulation, the angular variation will be less on account of the heavier fly-wheel called for by the formula. The cross-currents, on the other hand, remain the same for a given type of engine regardless of the regulation of the alternators. With single-crank engines these currents will be somewhat heavier than with cross-compound engines, and with multi-cylinder engines a trifle less. The difference in the latter case will hardly be sufficient to demand a separate formula, and the same may be said of vertical as compared with horizontal types of engines. With single-crank engines, however, the maximum angular variation should be determined and if the design of the engine is such that the variation in a single engine materially exceeds $\pm$ three electrical degrees, it would be advisable to modify the constant in the formula to a slight extent.

While there are apparently no disadvantages connected with the use of relatively light wheels, there are, at least, two distinct advantages that should not be overlooked. We have already seen that a light wheel means a high natural frequency for which it is relatively easy to get the engine governors to behave properly. In practice this is a very real and important advantage, and one not to be lightly dismissed.

A considerable saving in first cost may also be affected by using lighter wheels, especially in the case of slow-speed units, where the amount of iron that may be saved in the fly-wheel foots up to quite a respectable sum At the same time the general wear and tear upon the bearings of the engines are lessened.

We believe, therefore, that the formula given above may be used with perfect safety in predetermining fly-wheels for direct-connected steam-engine drive, with the following exceptions. For high speeds the wheels obtained, while meeting all electrical requirements, would hardly be heavy enough to give the engine a proper mechanical balance, and in such cases

heavier wheels, as determined by the engine builders, should be used. Variations of the formula will also suggest themselves in individual cases. Thus, for instance, with engines giving an exceptionally even driving torque connected to alternators of excellent regulation, the permissible ratio between natural and forced frequencies might be advanced to 0.75 or even more without serious risk of encountering resonance phenomena or of introducing troubles of other origin. With single-crank engines, on the contrary, it will occasionally be necessary to use a somewhat heavier wheel than the one indicated by the formula.

To sum up our main conclusions, we may say that the fly-wheel—as distinct from the assistance given either by the engine governor or the damping of the unit—is impotent to ensure satisfactory synchronous operation. Except for these two influences, the inherent tendency toward cumulative surging existing in the unit would predominate, and parallel running would be impossible.

It also seems advisable to use a somewhat lighter fly-wheel than would be considered conservative practice to-day. This greatly facilitates the adjustment of the engine governors while it does not decrease the stability of the system. For it would appear that the electrical damping of the units (which varies with their natural period and consequently with the fly-wheel) at least retains its relative strength as compared with the inherent tendency to surge for wide variations in weight of wheel. Therefore, if the damping is sufficient to hold the tendency to surge in check when a heavy wheel is used, it remains so for a light wheel. This argument applies to a change in weight of wheel for a given generating unit only, and should not be construed as one in favor of increased angular variation as such.

We also find that electromechanical resonance is a serious danger that must be avoided by making a proper choice of fly-wheel. A wheel selected with this end in view is at the same time satisfactory for general operating purposes, provided there is sufficient damping in the unit to check the inherent tendency to surge.

If we inquire, in concluding, what fly-wheel capacity suggests itself for direct connection to gas-engines, it must be said that it would be a little venturesome to advance a cut and dried rule at present in view of the limited practical experience with this type of prime mover. By analogy with steam-engine experience, however, it may be said that light fly-wheels and vigorous electrical damping is the combination that is most likely to win out for this class of work.

[For discussion on this paper, see page 461.]

BLANK
PAGE

A paper presented at the 187th Meeting of the American Institute of Electrical Engineers, New York, May 17-18, 1904.

Copyright. 1904. By A. I. E. E.

PREDETERMINATION OF SPARKING IN DIRECT-CURRENT MACHINES.

BY W. L. WATERS.

Speaking generally, dynamo design did not become an art until after the old two-pole smooth-core Siemens and Edison machines came into extensive use for lighting. The original design of these machines was more or less guesswork; but after a few machines had been made to run satisfactorily the designer was able to lay out a complete line of machines, designing them partly by eye and partly by some empirical rules, which he decided on as he built successive machines. The armatures were designed more from a mechanical than from an electrical standpoint, the length being limited by the stiffness of the shaft rather than by questions of commutation. The armatures were not ventilated and the output was necessarily limited by heating. The armatures being of the smooth-core type, the self-induction of the armature coils was so small, even with the length of armatures in general use, that usually it was not necessary to consider it in connection with the sparking of the machine. It was, however, generally recognized that if the magnets were too weak the machine was likely to spark, so the length of the air-gap was usually determined by some empirical rule obtained by experiment. When slotted armatures were adopted extensively they were designed along the same lines as smooth-core armatures. These armatures were so badly ventilated that the output was limited by heating to about one half that of a modern armature; but in spite of this it was found necessary to use carbon brushes to obtain good commutation.

To economize in dies several different lengths of armatures were frequently built on the same diameter, and to economize

space the armatures were often built smaller in diameter and longer than they otherwise would be. Experience with these different forms of armature made it very evident that a long armature had a greater tendency to spark than a short one; this became especially noticeable as the ventilating of armatures was improved and the output increased, so as to take advantage of the cooler running.

Up to this time a great deal had been written on the theory of commutation in dynamos, but had been ignored by the practical designers who had more faith in experimental results. This bad behavior of long armatures as regards sparking called attention to the theoretical work, and designers began to consider whether or not the self-induction of the commutated coil did not, after all, decide the amount of current the machine would carry without sparking. In the first attempts to take into account the self-induction of the commutated coil, the self-induction of a one-turn coil was considered as being simply proportional to the length of the armature core; that is, the shape and size of the slot, the number of coils per slot, and the self-induction of the end connections—all were neglected. This gave a very simple formula for the self-induction:

$$L = ln^2.$$

Where l = length of armature

n = number of turns per coil,

And the self-induction e.m.f. of commutation (the reactance voltage as it was called) which is an estimate of the difficulty of commutating the current, was given by

$$E = l\, n^2\, I\, f$$

I being the current per coil and f the frequency of commutation.

This formula gave good results when applied to machines designed along the same general lines. The allowable value of the reactance pressure could be obtained from experiment on one machine and used in the design of other machines. But, if applied to machines which were designed differently, the formula showed wide discrepancies; so it soon became recognized that the formula was at best only a rough approximation.

Early slotted machines were designed with one coil per slot; two coils per slot obviously saved insulation space and was soon tried, but it was found that generally every other bar on the commutator became badly marked.

As it was imperative to save space in car motors, three coils

per slot were adopted, and in extreme cases four, or even five coils per slot were used. It was generally found, however, that whenever more than one coil per slot was used some of the commutator-bars were marked, and that it was possible to count the number of coils per slot by the recurrence of the marking on the commutator. This marking was attributed to the inequality caused by using a small number of slots, and so the general rules were adopted—to use as many slots as possible and to make small machines with one coil per slot and large machines with two coils per slot.

It was also noticed that the dead coils necessary in certain multipolar wave-windings often caused some of the commutator-bars to be marked; this was naturally attributed to the dissymetry produced in the winding, and it became generally recognized that anything tending to produce inequality in the commutation conditions, such as few slots or many coils per slot, or dead coils, tended to make perfect commutation more difficult.

With increased competition came the necessity of cheapening the cost of building these machines; designers then returned to the construction of several coils per slot. In reducing the amount of copper on the armatures to save in the cost of material, it naturally happened that shallow slots were used. And it was found that with these wide and shallow slots it was possible to obtain good commutation with several coils per slot, under conditions where it would be quite impossible with the old deep and narrow slots. Obviously this was due to the lesser self-induction of a wide slot compared to a narrow one, and it was soon acknowledged that the shape of the slot should be considered in calculating the self-induction of the commutated coil.

When designing an armature for small self-induction it would be natural to make it large in diameter and short in length; that is, with a large pole-pitch. But in carrying this to an extreme it was found that it did not give the good results expected. It was suggested that this result was due to the fact that the self-induction of the end connections had been neglected and that in armatures with large pole-pitch and short length of core, the self-induction of the end connections was comparable with that of the conductor embedded in the slots.

In the light of these experiences it is evident that the design of a direct-current machine in regard to sparking is a compromise

between a number of conflicting conditions. It is not possible to obtain a formula which will give a strict measure of the commutating qualities of all machines; but by taking into consideration the more important conditions which effect the sparking it is possible to obtain a formula which will give fairly accurate results when applied to machines similarly designed, and which will give some idea of the sparking when applied to machines of widely different design. Such a formula, when it has been applied to a number of machines of different types, so that the allowable values for the sparking constant have been determined, can be taken as a fair working formula, and can be placed in the same category as empirical formulas for determining the regulation of alternators. Such formulas are not intended to reduce the designing of machines to mere slide-rule work, but are intended simply to give an idea as to the experimental results to be expected from individual design.

As outlined above, the most important conditions to be taken into consideration are the self-induction pressure of the commutated coil and the inequalities introduced by the conditions of commutation.

I.—Self-Induction Pressure.

This is given by the formula; V = self-induction of one coil times number of coils commutated in series times current in coil times frequency of commutation.

The self-induction of one coil = (self-induction of one conductor embedded in the slot + self-induction of one end connection) times (number of turns per coil)^2.

The self-induction of one conductor embedded in the slot = $l\,k$. Where l is the length of the core and k is a constant depending on the dimensions of the slot.

By determining the self-induction of a large number of slots we find that this constant k can with sufficient accuracy be taken as a function of the ratio

$$r = \frac{\text{width of slot.}}{\text{depth of slot.}}$$

A curve can be plotted connecting r and k, determined experimentally from tests on a number of armatures; such a curve is shown in Fig. 1.

Take the self-induction of the end connections = length of end connections times constant c'. And as the length of end connection is approximately proportional to the pole-pitch this can be written with sufficient accuracy = $p\,c$.

Hence the self-induction of one coil $= n^2 (l\,k + p\,c)$.

The number of coils commutated in series, N, is, of course, one in a parallel or lap-wound armature, and equal to the number of pairs of poles in a series or wave-wound armature.

The current per coil I in a series or wave-wound armature is equal to one half the total current in the machine, while in a parallel or lap-wound armature it equals the total current divided by the number of poles.

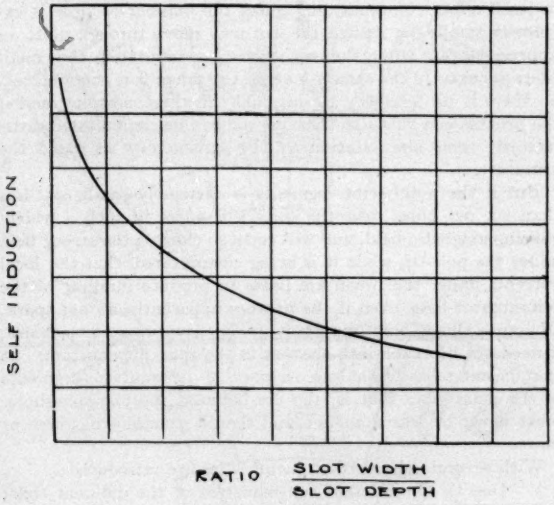


FIG. 1.

The self-induction pressure of the commutated coil is then given by

$$V = n^2 (l\,k + p\,c)\,N\,I\,f$$

Where f = frequency of commutation = number of commutator-bars times speed in rev. per min.

The width of the brush is neglected in calculating the frequency of commutation, since it is found by experiment that within the ordinary limits of practice the thickness of the brush has no effect on the operation of a machine, unless the current

density is excessive. The probable explanation of this is that a thicker brush gives more time for commutation to take place; but it means that more coils are commutated at the same time, thus increasing the self-induction effect. These two effects apparently counterbalance each other to a great extent.

II.—Inequalities Due to Conditions of Commutation.

These are due to the use of a few slots; more than one coil per slot; and to dead coils.

If there is only one coil per slot the use of few slots does not in itself affect commutation, unless the number of slots is extremely small; for though the slot may move through quite an appreciable arc while the coil is being commutated, the conditions are exactly the same for every coil when it is commutated. So there is no tendency to inequality in the conditions, and if the brushes can be set so that one coil can be commutated satisfactorily then commutation will be satisfactory all round the armature.

But if the number of segments is extremely small, say less than six per pole, then the coils will move in such a widely varying magnetic field, and will come so close to the strong field under the pole-tip while it is being commutated, that the local currents under the brush are liable to produce marking of the commutator-bars even if the brushes apparently do not spark. Of course this is only important in very low-pressure machines; it need not be taken into account in the sparking constant. It is sufficient to say that the number of commutator-segments in the polar-gap; that is, the arc between the two pole-shoes, must never be less than two and should generally be three or more.

With several coils per slot inequalities are introduced:

1. Due to the different self-induction of the different coils;
2. Due to commutation under different conditions.

The self-induction of all the armature coils will be the same when there are only two coils per slot, as it is obvious that the configuration of the conductors and neighboring iron is the same for both coils. But when there are three or more coils per slot the self-induction of the various coils will vary, as they occupy different relative positions in regard to the iron; the self-induction of the center coil will be less than the self-induction of the outer coil. Investigating conditions at the point of commutation in a modern generator by means of a pilot-brush, it is found that in practically all cases commutation goes on at a point where there

is no resultant magnetic field; that is, at a point where the armature field just counterbalances the field due to the magnets. In other words, there is resistance commutation; the armature current is commutated by the varying resistance of the brush, rather than by a reversing e.m.f. due to passing through a magnetic field. This being the case there is need to consider

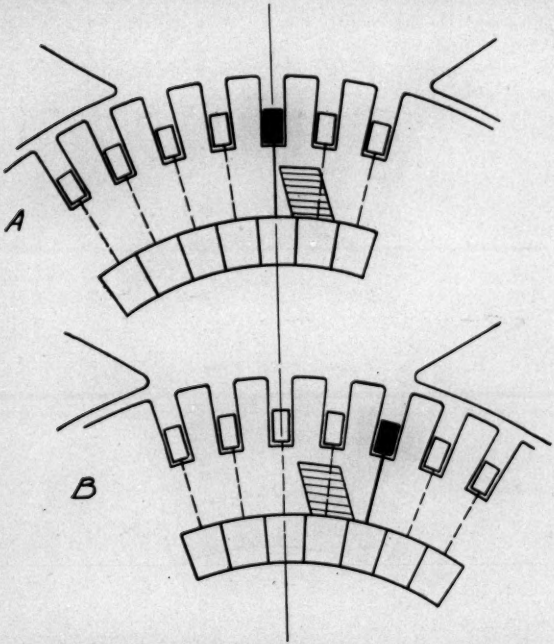


FIG. 2.—Showing position of armature at beginning and e ding of commutation period.

only the self-induction of those coils which have the greatest self-induction. If these are commutated satisfactorily by means of the varying resistance of the brushes, then those coils which have a smaller self-induction will also be commutated satisfactorily. Hence the variation in the self-induction of the coils

need not be considered and in the formula all that needs to be considered is the self-induction of those coils which have the greatest self-induction.

The chief inequality introduced into the commutation by having more than one coil per slot is due to the various coils in the slot commutating when they are in different magnetic fields. This is evident from Fig. 3, which shows the position of the armature when the first and the last coil in the slot are commutating.

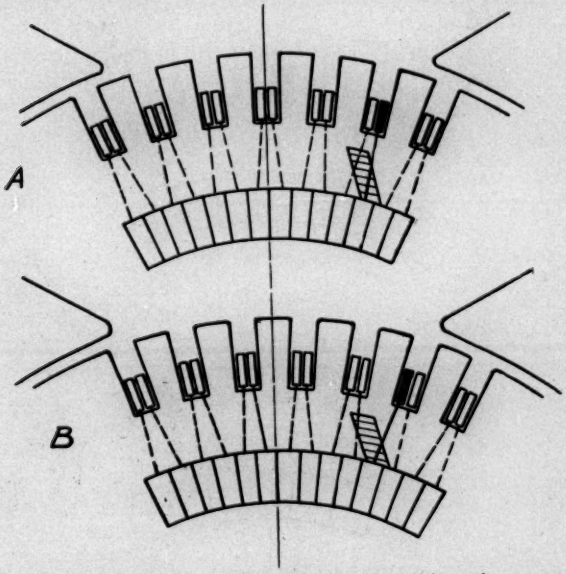


FIG 3.—Armature with two coils per slot showing positions of armature when the two coils are being commutated.

If the brushes are set so that the magnetic field is right for the first coil it will be wrong for the last one, and vice versa. So whenever the machine is loaded to its limit the commutating conditions will be so bad for some of the coils that in time some of the commutator-bars will become pitted and there will be that well-known regularly recurring marking of the commutator-bars.

The question now is how to take this inequality into account in the sparking formula. To do this, make the assumptions that the magnetic field varies uniformly from the neutral point to the pole-tip, and that in order to obtain perfect commutation

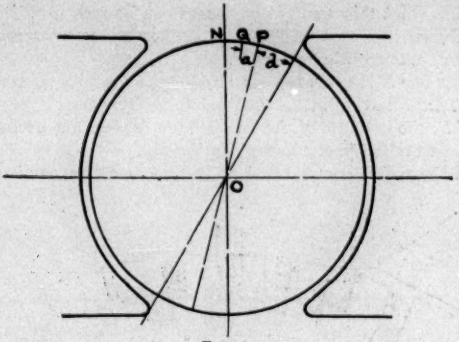


FIG 4

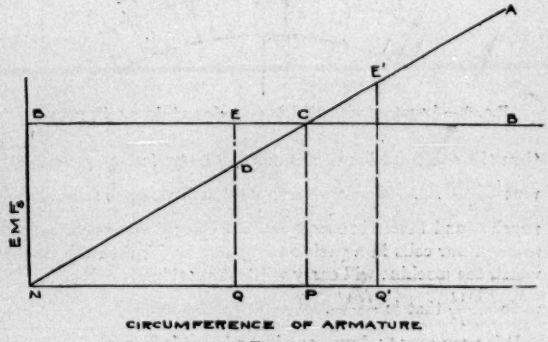


FIG. 5.

it is necessary to move the brushes from a position at the neutral point at no load to a position half-way between the neutral point and the pole-tip at full load. Calling the distance between the neutral point and the pole-tip $2d$, and assuming

the brushes fixed on the line $O P$ half-way between the pole-tip and the neutral point, then if any coil is commutated when it is at Q distant " a " from P, then it will only commutate perfectly a load $l - \frac{a}{d}$.

Just what this assumption means can be seen from Fig. 5.

Abscissa represent positions along the polar-gap corresponding to Fig. 4, and ordinates e.m.fs.

The line $N A$ gives the e.m.f. induced at various points by the conductor moving in the field due to the magnets.

$C P$, the ordinate of the line $B B$, gives the e.m.f. necessary to reverse the full-load current I in the coil.

If the coil is commutated at the position Q instead of at P

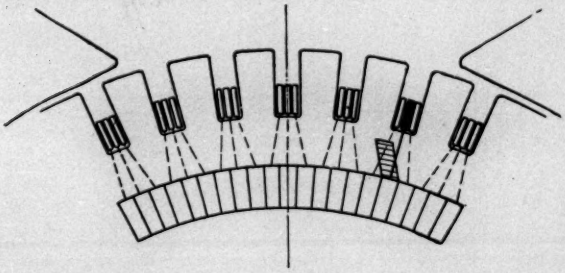


FIG. 6.—Armature with 20 slots per pole and three coils per slot.

then the commutation conditions will be perfect only for a current $\frac{D Q}{C P} \cdot I$. Hence we assume that if we have several coils per slot, and that if in consequence of this we have to commutate some of our coils in a position $E Q$ and $E' Q'$, then the current which the machine will carry without sparking is reduced in the ratio $\frac{D Q}{C P}$ that is $\frac{N Q}{N P}$.

It is very easy to figure out just what this inequality amounts to in any particular case. Take 20 slots per pole, 3 coils per slot, pole-face = 75% of pole-pitch.

There are 2.5 slots between the neutral point and the pole-tip. Assuming that the conditions are perfect for the center coil, the outer coils are 0.333-slot pitch out of this most favorable position.

And 1.25 slots corresponding to variation from no load to full load, hence an equality of 0.333-slot pitch gives an inequality factor $\frac{0.333}{1.25} = 0.26$. Hence the sparking constant should be multiplied by the inequality factor 1.26.

Curves can very easily be plotted for different numbers of slots per pole, and coils per slot, in order to facilitate the calculation of this inequality factor.

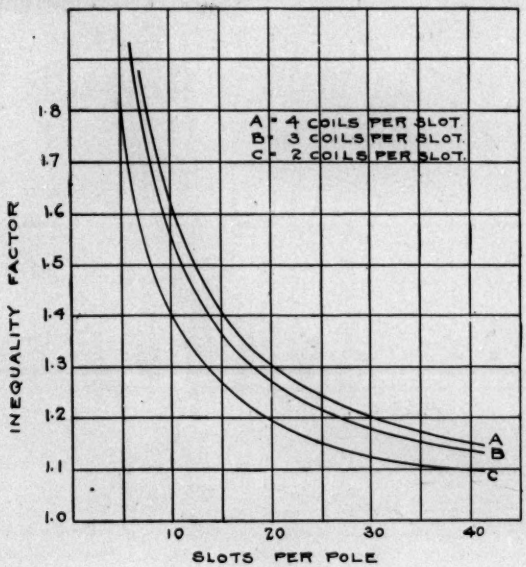


FIG. 7.

The assumptions on which this calculation is based are to a great extent rational, and though we cannot pretend that the calculation has a rigid basis, yet it is probably as correct as the other sparking calculations, and used with discretion it gives fairly reliable results.

The inequality introduced by using a dead coil on the armature is similar to that due to several coils per slot. The dead

coil produces a break in the uniformity of the winding; and if the position of the brush is correct for commutation of the coil immediately on one side of the dead coil then it will be just one segment out of the correct position for the coil immediately on the other side of the dead coil. The inequality introduced can be calculated, and allowed for in the sparking constant exactly in the same way as we allow for the inequality due to

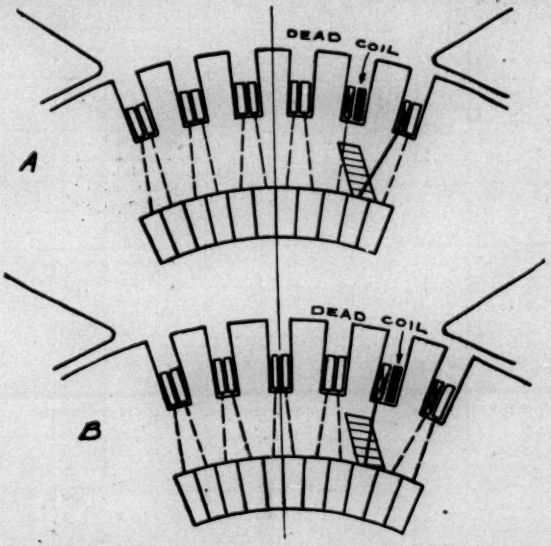


FIG. 8.—Armature with dead coil showing positions of armature when the two coils next to dead coil are being commutated.

several coils per slot. Assuming that the brush is in a mean position then it will be just half a segment out of position for the two coils which are next in position to the commutated coil.

Making the same assumptions as before; if there are n commutator-segments per pole, and if the pole face = 75% of pole-pitch then the inequality is equivalent to $\frac{8}{n}$. Thus if there are 20 segments per pole a dead coil produces an inequality equal

to 40% of the load, and the inequality should be introduced into the sparking constant by the factor 1.4. A curve can readily be plotted between the inequality factor and the number of coils per pole. Such a curve is shown in Fig. 9.

Combining all the different factors which affect sparking we get our complete formula for a sparking constant.

$$C = n^2 \ (l\,k + p\,c)\,N\ I\ f\ P\ Q.$$

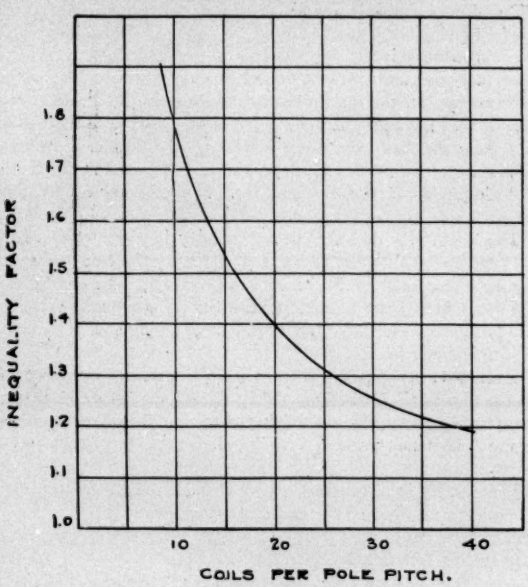


FIG. 9.

P being the inequality factor resulting from a number of coils per slot.

Q being the inequality factor resulting from a dead coil.

This formula is not put forward as being scientifically exact, but as an empirical formula which has gradually been built up as the result of experience, different terms having been added to the formula from time to time as it was found necessary to take different conditions into account. As the formula stands

it gives excellent results. When we know the value of C we can allow for the particular design of machine we are dealing with.

The relative values of C that have been found allowable in different cases are somewhat as follows:

2-pole	20
4-pole, series wound	35
6-pole, " "	50
4-pole, multiple wound	30
6-pole, " "	35
gradually increasing to	
24-pole, multiple wound	50

Of course, all the machines in each class are designed alike; that is, they have approximately the same densities in the teeth, and have the ratio of ampere-turns per pole on the armature (armature reaction) to the ampere-turns required for the teeth and air-gap approximately constant. If these vary much it is impossible to get consistent results.

The brush-gear and the current density in the brushes also play an important part in the sparking. If the brush-gear is weak mechanically, or if the commutator is in bad condition, the machine is sure to spark. And with ordinary-grade carbons the brushes will usually glow when the current density reaches 50 amperes per sq. in.

The shape of the pole-tips has some effect on the operation of the machine. But so long as they do not come too close together and so long as they are shaped so that there is a commutation field which varies gradually, the exact shape need give us no concern.

The density in the armature core (behind the teeth) has also a considerable effect on the allowable sparking constant. If the core is highly saturated it can be run with a constant considerably higher than if it is unsaturated.

Assuming that all these conditions are uniform and satisfactory, the variation in the allowable value of C shows that the formula does not take into account all the conditions that affect the sparking, so the formula must be used with considerable discretion. It cannot be claimed that the formula is in any way accurate, but it certainly is an empirical working formula, capable of giving very good results when carefully used, and as such it is put forward.

[For discussion on this paper, see page 443.]

A paper presented at the 187th Meeting of the American Institute of Electrical Engineers, New York, May 17–18, 1904.

Copyright, 1904. By A. I. E. E.

EFFECT OF SELF-INDUCTION ON RAILWAY MOTOR COMMUTATION.

BY E. H. ANDERSON.

This paper deals with fundamental features of railway motor commutation. Oscillograph records are employed to illustrate these features and no mathematical deductions are attempted. I would call your attention to the following:

1. The pressure produced by interrupting the line current flowing through the conductors connected to two adjacent commutator-bars, or what might be termed reactance volts of commutation based upon line current.

2. The pressure produced by interrupting local current which is additive to that produced by interrupting the line current, and the causes for the local current.

Direct-current railway motors are usually designed for 500 volts, having series drum distributed armature windings connected directly to the commutator; have definite polar projections and field-coils, the brushes being fixed in a mechanical neutral and suited to operate equally well in both directions of rotation.

Reactance pressure of commutation of line current may be calculated directly as any ordinary reactance, depending upon the shape of slot, length of iron in armature body, speed, kilowatts, armature diameter, frequency, etc. From any general expression for this reactance volts, there will appear in the numerator kilowatts and in the denominator amperes; which is to say that the greater the amperes, the less the reactance volts—at first seemingly absurd, but when it is considered that all other values are constant the expression means that the greater the amperes the less the pressure, and that the reactance

pressure of commutation of line current decreases as the pressure of the motor; in brief, this means that a motor of identically the same design will commutate better at 250 than at 500 volts. This is a matter of everyday personal experience, and needs no further discussion.

The point brought out in the above is that high-pressure machines are difficult to build; and good commutation with reasonable cost is unfortunately limited to relatively low working pressures, low compared with the power involved.

Taking the frequency of commutation as the relation of the number of commutator-bars to the width of brush, a low value of reactance volts is calculated. For good commutating ma-

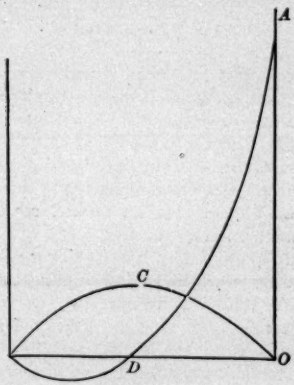


FIG. 1.

chines this value is a fraction of a volt. Reactance pressure between the commutator and the brush, as indicated by the spark, is evidently much higher, and oscillograms hereafter given show this to be so. Fig. 1 appears to me to explain this. Estimating on a uniform change of current throughout the width of the brush, we get a maximum value represented by *C D*. Consider that for the first half of the brush the line current is being increased by the addition of local current, then the pressure across the first half of the brush will be negative; as the commutator bars proceed across the brush the sign of the pressure reverses. In the latter part of the brush the current

decreases, the change in current becoming more and more rapid as the bar nears the edge of the brush, until at the point of rupture the change of current is very great, the frequency thus represented being many times that of the frequency indicated by the number of commutator-bars to width of brush, consequently we get a value represented by $O'A$ instead of the value $C'D$.

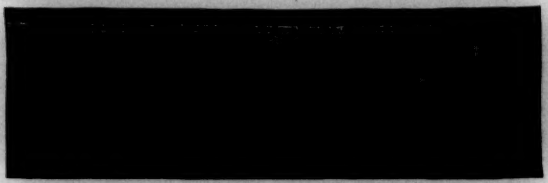
OSCILLOGRAM 1.
General Electric railway motor. Pressure between two exploring brushes 7-32 in. apart, one 1-16 in. behind motor brush. 304 amperes in field and armature; 453 volts, 482 rev. per min.

Oscillogram 1 shows the pressure between two exploring brushes, one placed under the brush and the other 1/16 in. ahead of the brush. The maximum values are, as indicated, approximately four volts, and since there are evidently some losses in the contacts of the exploring brushes, the real pressure may be more than indicated. The motor on which this oscillogram was taken is rated on the hourly basis at approximately 300 amperes and 500 volts. The armature is designed with five coils—10 conductors—per slot, and while this may apparently be a radical distribution of conductors, the values in the oscillogram of the pressure of commutation over all bars are approximately the same. This indicates that even with five coils per slot the armature can be so connected as to equalize the commutation for all bars, and still got the advantages of five coils per slot construction.

The pressure produced by interrupting the local current is of course dependent upon the frequency as above outlined in Fig. 1; in fact the whole current, line and local, produces the reactance volts of commutation. This local current is produced by a pressure generated in the conductors connected to the commutator-bars which lie under the brushes. This pressure is due to the

shifting of the field caused by the armature magnetizing effect, and is influenced somewhat by the volts per bar of the motor. It will be appreciated that this local current must be cut down as much as possible, since the brushes are always in mechanical neutral, and consequently railway motors have, as a rule, low armature turns and very high flux and field turns compared with those in the usual direct-current generator.

OSCILLOGRAM 2.
General Electric railway motor. Pressure between one brush or motor and an exploring brush. 300 amperes, 520 rev. per min. Run as a motor.



OSCILLOGRAM 4.
General Electric railway motor; 300 amperes in field, 500 rev. per min. Carbon brushes removed. Pressure between commutator-bars, 5-6.

Referring to Oscillogram 2, the minimum pressure between the motor brush and the exploring brush is higher than can be accounted for by the IR drop of line current—evidently there is added to the line current enough local current to produce this drop. Since in large motors the local copper circuit is of low resistance compared to the brush contact, nearly all the energy of the local current is delivered as heat on the commutator. Should the motor be very large, the stability of the field

relatively to the armature must be great in order to limit the local current to a low value, else the motor will spark and glow at the brushes.

Conversely, on small machines the resistance of the local copper circuit may be high compared to the carbon contact resistance. The same volts induced in the local circuit produced by the distortion of the field do not cause proportionately great local currents to flow, thus greater reactance pressure and greater current density in the brush can be used in design.

Oscillogram 3 is a record of pressure between two commutator-bars with full field excitation, the armature being driven and no current flowing through it, showing the distribution of the flux.

OSCILLOGRAM 3.
Pressure between commutator-bars 4-5; 300 amperes, 465 volts, 497 rev. per min.

OSCILLOGRAM 5.
Pressure between commutator bars 1-2; 90 amperes, 475 volts, 950 rev. per min.

Oscillogram 4 is the same as Oscillogram 3 except that the armature is loaded and the machine runs as a simple series motor with full rated current. Note that the flux is shifted slightly and the pressure peaks of commutation are shown near the zero line. Several pressure peaks are shown which are evi-

dently caused by the mutual induction, other conductors in the same slots being commutated.

In Oscillograms 3 and 4 two adjacent commutator-bars were connected to collector rings and the record of pressure taken between these.

Oscillogram 5 is taken under the same condition as Oscillogram 4 except that the load on the motor is slightly less than one-third the rating. With one-third excitation the densities are approximately one half, and from Oscillograms 4 and 5 it will be seen that the distortion of the flux at one-third load is much greater than with full load, indicating that the stability of the flux is quite essential to good commutation. Theoretically this stability can be gotten in two ways:

1. The usual method of great saturation.
2. By compensating for the disturbing element (armature reaction).

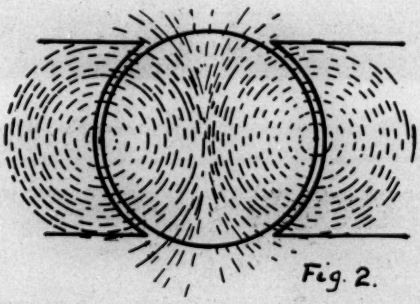


Fig. 2.

Theoretically the latter points to a motor with distributed winding on the field, pole-faces of greater pitch, equal density over the pole-face, relatively few field turns, and the possibility of higher pressure motors.

Fig. 2 shows the effect of armature m.m.f. when there is no main flux and no compensation.

Oscillogram 6 shows the pressure between two commutator-bars when there is full-load current in the armature and no current in the field, the motor being driven at approximately rated speed. It will be seen that this agrees with Fig. 2. Were the armature completely surrounded with iron pole-face, the

peak of the wave would occur where the brushes are located. The position of the brushes is indicated by the several minor peaks of pressure caused by the commutation of the line and the large local current.

OSCILLOGRAM 6.
Pressure between commutator bars 5-6. No current in field. 300 amperes in armature, 500 rev. per min.

OSCILLOGRAM 7.
General Electric railway motor. No current in field. Pressure between one brush of motor and an exploring brush; 307 amperes in armature, 530 rev. per min.

Oscillogram 7 indicates very forcibly the action of the brushes when running with full current in the armature and no field flux. The pressure between the motor brush and the exploring brush just ahead of the motor brush is at the minimum, six to eight volts, and since only about one volt can be accounted for by the $I R$ of the line current, there is probably a density in the brush contact six to eight times as great. The brushes under test actually get very hot and act badly. It will be seen that there is an average drop of about 10 volts and with 300 amperes line current will give 3 kw. which will account for the heating of the brushes.

Oscillograms 6 and 7 and Fig. 2 will be referred to later where their practical value will be seen.

There is another phase of this subject which is rather new in the electrical world and of considerable importance to engineers and to operators of large direct-current motors. I refer to the proper design of these large direct-current motors so as to eliminate as much as possible the tendency of motors to flash-over when running at free speeds and light currents, the current being interrupted and contact restored again with full pressure across the motors. For some time I have had the opportunity and pleasure of investigating these phenomena for the General Electric Company. The investigation has been continued over considerable time, and a great many tests of almost every character have been made. A few of the fundamentals will be illustrated by oscillograms.

Field-coils consisting of ribbon-copper wound into mica-insulated brass or metallic spools, the last turn of each section riveted to the turn below, forming a band which holds the winding and terminal firmly in place, will, for lack of a better name, be called *standard fields*. We shall also take another construction of field winding where the brass or metallic spool is not used, or approximately the same condition where the spool is cut so as not to form a continuous metallic belt around the pole. The last turn in each section instead of being sweated and riveted to the turn below is insulated therefrom, thus doing away with the copper belt round the pole. Coils constructed in this manner, will, for lack of a better name, be called *special fields*.

It was found that motors with exceedingly good commutation at normal loads and even on overloads at rated pressure, and motors which would commutate without flashing-over with full-load current at double rated voltage, had a peculiar tendency to flash-over when the current was changed rapidly or the circuit interrupted and made again with full pressure on the motors. This phenomenon almost disappeared at heavy loads; that is, at low armature speeds, but increased and became serious at light free-running speeds; that is, high armature speeds with light loads. The flashing pressure sometimes came within the range of high sub-station pressure. These phenomena were reproduced on the stand in various ways and the flashing points determined for a great number of conditions of load, time of interruption, character of contact points, etc. The flashing-over could be accounted for in two ways:

1. That the main flux of the motor changed very rapidly

(when current was applied at full pressure) through the frame; and since the armature coils lying under the brush would encircle the whole of this flux, a great transformer pressure would be induced in these coils causing large local current to flow in the coil and through the brush contact. On interrupting this current as the coil passed out from under the brush, there would be a flash across the mica from bar to bar; and there would be sufficient pressure to maintain it, consequently the line current would follow the local flash from bar to bar and thus flash-over.

2. That the predominating cause was the slowness of the main flux to respond to excitation, allowing a great rush of current. All metallic belts around the main flux acted as short-circuited turns and absorbed the excitation, only a small portion acting to create the main flux.

Since there would be little or no main field, the m.m.f. due to armature turns would create a considerable field where the brushes are located. If the speed were high enough and the armature amperes great enough, there would be produced a considerable e.m.f. in the local circuit under the brush, causing local current to flow. Commutation of local and line current would tend to cause flashing from bar to bar and a flash-over of the motor before the main flux rises to any appreciable value to aid in commutation.

Another way of looking at it is to suppose a motor operated at a constant pressure of say 500 volts. to have its field reduced to one third or one fourth of its value, the armature being speeded up three or four times its full field-speed, and a load of two to three times normal current put on the armature. Any one familiar with the operation of 500-volt machines will appreciate at once the likelihood of a flash-over.

In order to segregate these causes and find the value of each, the following tests were made:

The railway motor was driven at various speeds, the current through the field was interrupted and made with various maximum currents and pressures in the circuit. The armature was open-circuited, the brushes, however, being well fitted to the commutator. Should causes outlined above in 1 be ruling, flashing would be produced.

The speed and excitation under which these tests were conducted generated approximately 1500 volts across the commutator, and throughout the entire tests there was not even the

slightest sign of flashing, showing that the condition outlined in 1 was not in any way ruling, and that conditions outlined in 2 were by far the ruling causes of flash-overs.

The oscillograph was employed to record the current, pressure across the armature, and the pressure across the field. The tests were taken with standard field and with special fields, and are compared on the following oscillograms: an explanation of these will suffice to bring out the facts.

OSCILLOGRAM 8.
Standard field. Pressure across motor field. 67 amperes, 30 interruptions per min.

Oscillogram 8 shows pressure across the standard field when current is broken and circuit made again. At A current is interrupted and there is self-induction pressure which lingers for an appreciable time. At B the circuit is made again, the time from A to B is approximately one second, the motor running free on the stand at approximately one-third load and at double full-load armature speed.

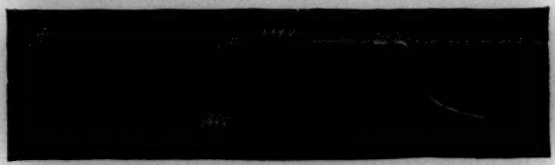
OSCILLOGRAM 9.
Special field. Pressure across field of motor. 538 volts, 60 amperes, 30 interruptions per min.

Oscillogram 9 is the same as Oscillogram 8 except the field-coils are special (all short-circuiting effects removed), the effects of the solid-steel frame, however, remaining. The particular point is that the self-induction pressure across the field-coils is more than twice as much with special fields as with standard

fields, and it will be seen later the maximum current with special fields is about half that of standard fields.

OSCILLOGRAM 10.
Standard field. 61 amperes, 30 interruptions per min.

Oscillogram 10 shows the pressure across the armature with standard fields. From A to B is about one second. The pressure gradually fell and at the end of one second there was still sufficient flux to give 101 volts, or about one fifth of the field. It will be noted that at B a sharp peak occurs which evidently is the self-induction pressure of the armature. As soon as the current has reached its maximum this pressure is zero. In the meantime, however, the main flux is rising slowly so that the e.m.f. wave drops down and continues to record the counter e.m.f. due to the main flux of motor. The action will be clearly seen by a slight analysis of the curve.



OSCILLOGRAM 11.
Special field. 60 amperes, 30 interruptions per min.

Oscillogram 11 is the same as Oscillogram 10 except the fields are special. Note how rapidly the main flux decreases, the pressure falls from 538 to 49 volts; to less than 1/10. Note also that the armature self-induction pressure record disappears and the counter e.m.f. due to main flux rises very rapidly.

Oscillogram 12 shows the current in the motor with *standard fields*. At A the current is interrupted; after a lapse of one

second the circuit was again made at B. The motor was running free at 61 amperes and when circuit was made again the current rose to a maximum of 303 amperes, a ratio of about five times the minimum and about 50% more than the hourly rating of the motor.

OSCILLOGRAM 12.
Standard field. 518 volts, 30 interruptions per min.

OSCILLOGRAM 13.
Special field. 538 volts, 30 interruptions per min.

Oscillogram 13 shows same as Oscillogram 12 except that the fields are special. The current was interrupted at A and after a lapse of one second the circuit was made at B. The noticeable feature is that the maximum current is less than one-half that in Oscillogram 12 and only about 70% of the rated current of the motor.

Compare Oscillograms 1 and 7. In 1 the motor is operating on a steady full load. The pressure of commutation indicated is in the neighborhood of 3.5. In Oscillogram 7 there is no field excitation and simply the full-load current is passed through the armature, the armature being driven at approximately full-load speed and the pressure from brush to commutator shows 10 to 12 volts. Should the speed have been 2.5 times the full-load speed, as occurs often in practice with the minimum free-running current and maximum current passing through the armature 50% more to twice as great as the full-load current, it is reason-

able to estimate that the pressure between brush and commutator bar of 45 to 60 volts may exist, or 12 to 15 times as great as when that motor is carrying a steady full-load current at full field and full pressure.

[For discussion on this paper, see page 443.]

BLANK
PAGE

A paper presented at the 187th Meeting of the American Institute of Electrical Engineers, New York, May 17-18, 1904.

Copyright, 1904. By A. I. E. E

ON THE CALCULATION OF LINE BATTERIES.

BY W. E. WINSHIP.

Storage-batteries have found a legitimate use in electric railway work for the purpose of maintaining the line pressure at points distant from generating stations. There is at present very little literature on this subject, and it is the purpose of the present article to discuss the calculation of such battery installations, and to compare in a general way the results with those which may be obtained by the use of copper. Independently of maintaining the pressure on the line, obviously something toward load regulation is obtained through the use of batteries.

Line batteries are installed in either of two ways; they may be fed over a boosted feeder with the average current which would be demanded from a sub-station maintained at the same pressure as the average pressure of the battery, the latter charging or discharging the difference between the instantaneous current and that supplied over the boosted feeder, or they may be simply floated on the line; that is, connected across the feeder and rail, in which case the battery will charge when the demand on the line is light and discharge when it is heavy. Such floating batteries are a close analogy to an air chamber, or a stand-pipe on a pipe line. Obviously, if the demand varies but very slightly, there is no occasion for such a reservoir; just as obviously if the demand is variable it would be a decided advantage.

The calculation of batteries to be fed over a boosted feeder from the power-house is extremely simple when the section operated on the battery is insulated from the other feeders from the power-house. We have simply to install the number of cells corresponding to the average pressure desired at the battery

location, and, when we determine the average demand at this point, decide on the size of feeder advisable and hence determine the amount of "boost." The size of the feeder should involve, however, the consideration of losses in transmission, and a balancing of this loss against the amount necessary to expend for copper.

With a floating battery the determination is not quite so obvious, and the writer purposes to take up this calculation more in detail.

We consider, first, the case of a concentrated load at a point between two stations at different pressures. Let V_1 be the pressure of Station 1; V_2 that of Station 2; I the load; r the resistance between Station 1 and the load; s the resistance between Station 2 and the load; R, the total resistance; I_1 and I_2 the currents furnished by Stations 1 and 2 respectively. Then by a consideration of the drops from 1 and 2 we have

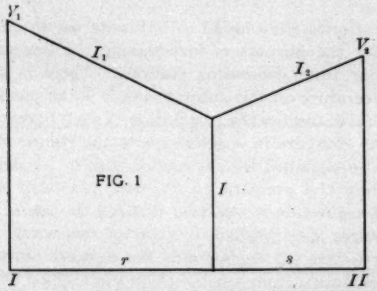


FIG. 1

$$r I_1 - s I_2 = V_1 - V_2; \text{ also,}$$

$$I_1 + I_2 = I; \text{ hence}$$

(1) $$I_1 = \frac{[s I + (V_1 - V_2)]}{R}$$

(2) $$I_2 = \frac{[r I - (V_1 - V_2)]}{R}$$

If we have distributed loads of $i_1, i_2, i_3, \ldots i_n$ amperes and the resistances from Stations 1 and 2 and the points of location of these loads are $r_1, r_2, \ldots r_n, s_1, s_2, s_3 \ldots s_n$, respectively where $r_m + s_m$

$= R$, the resistance between Stations 1 and 2, a generalization of equations (1) and (2) will be

$$I_1 = \frac{\Sigma s i + (V_1 - V_2)}{R} \tag{3}$$

$$I_2 = \frac{\Sigma r i - (V_1 - V_2)}{R} \tag{4}$$

Obviously,

$$I_1 + I_2 = \frac{\Sigma r i + \Sigma r i}{R} = \Sigma i = I. \tag{5}$$

where I is the sum of all the currents. It is possible to interpret these equations very simply in a geometrical diagram.

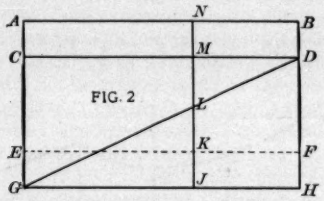


FIG. 2

In the figure $C\,G$ represents I, the total current; $G\,H$ is the resistance R; $A\,C = M\,N = K\,J = \frac{(V_1 - V_2)}{R}$ = current which would flow from Station 1 to Station 2 with no load on the line. $G\,D$ is the diagonal of the figure $C\,D\,H\,G$, and $G\,J = \Sigma\, r\, i / \Sigma\, i$. The point J thus corresponds to the center of gravity of the loads. We have then $L\,N = I_1$ and $K\,L = I_2$. The application of this diagram we shall take up below.

Preliminary to the determination of the proper location of a floating battery we shall next consider the problem: with a definite current, I, on the line at various points what is the value and location of minimum pressure? We preserve the preceding notation.

We have as the drop in pressure from Station 1

$$D = r_1 I_1$$

or from equation (1) inserting the value of I_1

$$D = -\frac{r_1^2 I}{R} + r_1 \left[I + \frac{V_1 - V_2}{R} \right]$$

and therefore, as the pressure on the line at any point,

$$V = V_1 - D = \frac{r_1^2 I}{R} - r_1\left[I + \frac{V_1 - V_2}{R}\right] + V_1$$

This equation has the form

$$y = A x^2 + B x + C$$

and represents a parabola whose axis is parallel to OY. If we make the substitution $x = x + e$ we may make this equation take the form

$$y = A x^2 + E$$

(6) if $$e = \frac{I R + (V_1 - V_2)}{2 I}$$

and

(7) $$E = V_1 - \frac{[I R + (V_1 - V_2)]^2}{4 I R}$$

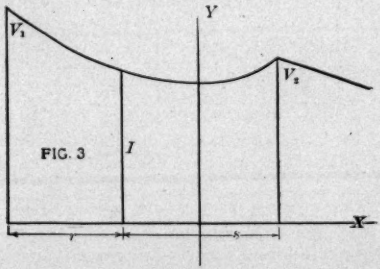


FIG. 3

E is then the minimum pressure on the line with the current I, and e is its distance from Station 1 in ohms. Beyond Station 2 the drop will be simply the resistance multiplied by the current.

In general, with definite feeder and return circuit the best results as far as line pressure is concerned will be obtained by making the minimum pressure with maximum demand between Stations 1 and 2 equal to the minimum beyond 2. With a number of cars on the line it is not of course sufficient to consider the total current as concentrated at the center of gravity of all the currents and then calculate the drop to this center of gravity; determined in this manner it would be much too large. We must consider the separate currents and then determine the minimum pressure. The best point of location of the bat-

tery is, in any case, readily determined. It will plainly depend on grades and accelerations, but it may be said that the point is ordinarily between 0.66 and 0.75 of the distance from the power-house to the end of the line.

The open-circuit pressure of a battery varies from 2.05 to 2.12 volts per cell according to the acid density, temperature, and state of charge. It is usual for regulation work to allow a battery to float in approximately a three-quarter charged condition as the efficiency is best in the neighborhood of this point and the pressure fluctuations on charge and discharge are less. We shall take 2.1 volts per cell as the proper value on open circuit—it is actually a trifle less—and assume the battery as equivalent to a station operating at a pressure of 2.1 times the number of cells. The pressure will ordinarily vary on charge and discharge from 3% to 6% above and below this value, but since the battery will charge and discharge by correspondingly less amounts, our calculations will not be vitiated as far as the determination of the number of cells is concerned by taking the above value. We shall afterward point out the effect of the pressure variations.

Floating batteries are quite often installed, so that over a complete cycle of the car schedule they experience neither a net charge nor discharge excepting a certain amount necessary to make up the internal loss of the battery; this is, however, an extremely small amount, as the ampere-hour efficiency of a storage-battery is extremely good. In order for a battery to operate in this way all of the conditions of operation, including schedule, station pressure, feeder, etc., are fixed, and if any of these conditions are departed from the battery will either charge or discharge. It is obviously possible with a regular daily schedule, which may however vary from time to time during the day, so to install a battery that the net charge during the lighter hours will equal or slightly exceed the net discharge. This may be done by keeping the power-house at approximately a constant average pressure with a varying schedule, provided the battery has the proper number of cells; if, however, the net discharge over any maximum period exceeds the ampere-hour capacity of the battery, it will be necessary either to vary the pressure at the power-house or vary the number of cells of the battery with varying schedule conditions.

In this connection it is proper to note that the capacity of the battery should be reckoned approximately at the rate corresponding to the duration of all the net discharges, and not at

the rates at which the separate discharges occur. This is due to the recovery element of a battery; that is, if a battery is discharged at a high rate for a short time and then allowed to recover, and the same cycle is repeated a number of times, then the ampere-hour capacity of the battery on this work very nearly approximates the capacity at the rate corresponding to the total time elapsing.

Quite usually the conditions of operation are that in early morning and late at night the schedule is less frequent than during the major part of the day; during this latter time the loads vary at different times. Generally the calculation of a battery for this sort of schedule would be based on the determination of an average running current per car under different conditions. These values would be most suitably determined from station wattmeter readings, dividing by the pressure of the station, time elapsing between readings, and the number of cars. The battery should then be so calculated that it receives a net charge during the early morning and late at night, floating during the greater part of the day and discharging during the maximum hours. The net charge should slightly exceed the net discharge to make up for the inefficiency of the battery.

With reference to the formulas (3) and (4) and their geometrical interpretation in the diagram, Fig. 2, it is obvious that if we base our calculations on the number of cars distributed on the line, each taking the average current per car, then a battery installed at the point *II*, of average voltage V_2, so determined that $(V_1 - V_2)/R = JK = JL$ (that is, so that K coincides with L), will neither experience a net average charge nor discharge over an interval corresponding to a complete cycle in car schedule. If during any instant the current demand of the cars departs from the average values then the battery will charge or discharge according to the variation of these currents. It will be noticed that the center of gravity oscillates in general between certain limits even if we assume that the cars all take a constant average current. In any particular case it will appear, whether it suffices to take the point J as the average of the centers of gravity, or, if it will be necessary to take several different positions, according to the number of cars on the section *I* to *II*. In case the number of cars on the section varies from time to time it is convenient to calculate separately the components of the battery discharge and obtain the mean. In the calculations all cars beyond the battery are to be considered as concentrated at Station 2.

If a battery is to float absolutely; that is, stay at the same state of charge, an extremely simple pressure diagram may be drawn:

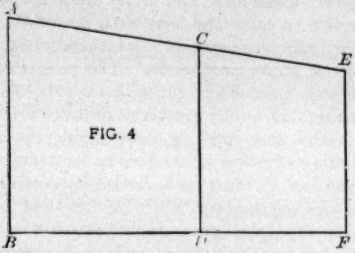


FIG. 4

Make $AB = V_1, BD = \frac{\Sigma ri}{\Sigma i}$ and $EF = V_1 - RI$; then $CD = V_2$.

The problem of a floating battery may take either of the three forms: (*a*) with a given feeder and rail circuit and definite schedule determine the pressure at which a battery will float; (*b*) assuming a definite pressure at the battery location, with a definite schedule, how much copper is necessary? or (*c*) with definite copper and return circuit and a definite schedule what will be the battery charge or discharge? We are in a position to solve each of these problems, or a combination of them.

In (*a*) we determine the center of gravity of the average running currents; then in the diagram we obtain $JK = JL$. From the relation $JK = JL = (V_1 - V_2)/R$ we obtain V_2. In (*b*), similarly, we obtain JL and from the same relation determine R. In (*c*) we obtain $JK = (V_1 - V_2)/R$ and obtain from the diagram $KL = JL - JK$, the battery discharge. We have the possibility of regulating arbitrarily either singly, or in combination, V_1 or V_2, perhaps even R, to accommodate for any schedule variation which we do not wish to impose on the battery capacity. To regulate V_2 we either cut in or out a certain number of cells or arrange certain cells for grouping, either in series or parallel.

The diagram, Fig. 2 shows also the extent to which the total instantaneous current demand comes on the power-house if we draw the diagram for the instantaneous currents of the separate cars. Very clearly, the nearer a heavy load is to the power-house the larger is the portion of this load furnished by it. If

the heavy currents are demanded near to or beyond the battery, the latter furnishes the major portion of the load. If grades and starts occur near the end of a line the battery will very materially steady the power-house load; and under these conditions it will often be possible to carry the load with less units, raising the load-factor of those in operation, and thereby decrease materially the cost of power production. The pressure variation of the battery is of particular influence in this determination. The power-house load will be greater than if the pressure did not fall as it actually does, and in determining the amount that either the battery or power-house does under definite conditions the actual value of V_2 must be assumed approximately.

In case a floating battery is to be installed between two power-stations, the calculation would be as follows:—calculate the currents $J\,L$ for the battery and each power-house separately; if I is the sum of these two currents, and the battery is to float, then we must make

$$\frac{(V_1 - V_B)}{R_1} + \frac{(V_2 - V_B)}{R_2} = I \tag{8}$$

where V_B is the battery pressure.

The condition that in addition to floating on a feeder system, the battery receives current over a boosted feeder, with the same track return, is also very simply calculated.

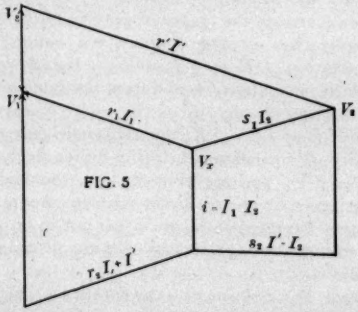


FIG. 5

Preserving the previous notation with the exception that we indicate the feeder and ground return resistances separately by subscripts $_1$ and $_2$ respectively, and indicating the booster pres-

sure by V_3, the resistance of the separate feeder by r' and its current by I', we shall have in the network the currents marked in the diagram, where also, (by a consideration of pressure drop),

$$V_x = V_1 - (r_1+r_2)\, I_1 - r_2 I'$$
$$= V_2 - (s_1+s_2)\, I_2 + s_2 I'$$

Or writing $r_1+r_2 = r$; $s_1+s_2 = s$ and $r_2+s_2 = R_g$, the resistance of the return, we obtain

$$(9) \quad r I_1 - s I_2 = (V_1 - V_2) - R_g I'$$

together with (10) $I_1+I_2 = i$.

The solution of these equations is

$$(11) \quad I_1 = \frac{\{s i + [(V_1 - V_2) - R_g I']\}}{R}$$

$$(12) \quad I_2 = \frac{\{r i - [(V_1 - V_2) - R_g I']\}}{R}$$

Where there are several loads, $i_1, i_2, -i_n$ the generalization of this solution is

$$(13) \quad I_1 = \frac{\{\Sigma\, s_1 i_1 + [(V_1 - V_2) - R_g I']\}}{R}$$

$$(14) \quad I_2 = \frac{\{\Sigma\, r_1 i_1 - [(V_1 - V_2) - R_g I']\}}{R}$$

The condition that the battery should float is $I_2 = I'$. Inserting this in (14) we obtain

$$(15) \quad I_2 = \frac{[\Sigma\, r_1 i_1 - (V_1 - V_2)]}{(R - R_g)}$$

The modification in the diagram, Fig. 2 is to make the line $A\,B = R - R_g$. It should be noticed that R is the resistance of the circuit exclusive of the boosted feeder.

The solution of our problem is therefore obtained by finding the value of I_2 and supplying this current over the auxiliary feeder.

The booster pressure we obtain from the diagram since we have

$$V_1 + V_3 = r' I' + V_2 + s_2 [I' - I_2] + r_2 [I_1 + I']$$

or assuming $I' = I_2$,

$$= r' I_2 + V_2 + r_2 i.$$

Generalizing for a number of cars on the line, the amount of "boost" is therefore

$$V_3 = r' I_2 + \Sigma r_g i - (V_1 - V_2)$$

We have thus developed a method of calculating line batteries under various conditions. To compare absolutely the results obtainable with copper and with batteries is impossible without taking up each problem and investigating it for itself, as there are too many factors entering into the comparison. We should consider first the costs of copper alone, and copper with batteries for equivalent line voltages; also the interest and depreciation in the two cases, together with the transmission losses. The battery should be credited with the influence which the load equalization effected would have on the cost of power production; and, also, the emergency value of the battery, in case of temporary breakdown, should receive consideration. This latter value is extremely difficult to express in a money equivalent. In some cases, however, it is so important as far to outweigh any question of economy of operation. It may be stated that with fairly long lines, say lines whose ends are six to ten or twelve miles distant from a power-house, and if the cars run are relatively few in number and heavy, a battery installation will generally cost less than equivalent copper. If grades and starts occur, principally distant from the power-house, the value of the battery as a load equalizer would nearly always justify its installation.

In any event, a careful comparison of the results which can be obtained with batteries should be made with the other feasible ways of obtaining the desired ends. In case of comparison with sub-station installations we must not forget that the battery requires almost no attendance in comparison with an alternating-current sub-station.

[For discussion on this paper, see page 457.]

A paper presented at the 187th Meeting of the American Institute of Electrical Engineers, New York, May 17–18, 1904.

Copyright, 1904. By A. I. E. E.

WAVE FORM VARIATIONS OF A LONG-DISTANCE LINE.

BY GEORGE H. ROWE.

The map, Fig. 5, shows the lines of the Standard Electric Company's system on which the following oscillographic curves were taken. At the head of the system, Electra, the power-house contains five 2000-kw. three-phase generators of the S.K.C. inductor type, each giving 2200 volts at 60 cycles per sec. These generators are supposed to have an inherent regulation of 3% on full non-inductive load, and 15.5% on full kilovolt-ampere load, 70% power-factor. The normal exciting current for full load, 100% power-factor, is 150 amperes at 2200 volts, with a limiting field-current of 250 amperes.

The Bay Circuit shown on Fig. 5 is fed from two banks of three transformers each, both high- and low-pressure circuits of which are Δ-connected. The ratio of transformation is 16.4, and therefore the line pressure is above or below 36 000, depending on the load and power-factor of the system. Besides the Bay Circuit, several mining circuits extend to neighboring mining camps in Ammador and Calaveras counties. The maximum length of these is about 30 miles. They are operated independently of the Bay Circuit at about 17 000 volts. The Bay Circuit lines, consisting of aluminum cables, extend to San José, a distance of 113.6 miles; to Oakland by way of Mission San José, a distance of 128.8 miles, and to San Francisco by way of Alviso a distance of 153 miles. The calculated charging current of the system at 40 000 volts is about 30.3 amperes on the assumption of a sine wave. From the generators this would mean 500 amperes line current.

In Fig. 6 will be found curves of observations taken on January 16, 1904, at Electra. The power curve is derived from 15-min-

ute readings of the integrating wattmeters and is probably considerably in error, both on account of the manner of taking and on account of the large leading current.

It is difficult to give an accurate idea concerning the nature of the load. At Stockton are two 150-kw. synchronous motor-generator sets. The San José division contains one 250-kw. and

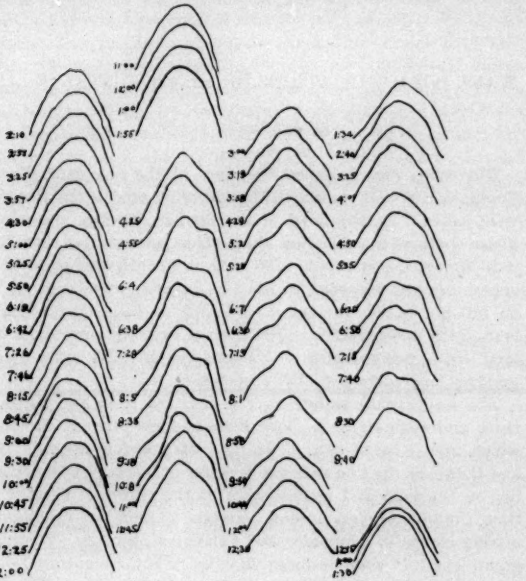


Fig 1 Electra — Fig 2 San Jose' — Fig 3 Stanford — Fig 4. San Francisco

one 150-kw. synchronous motor-generator set, both used for street railway and general power work, the generators being operated in parallel with a storage-battery. The direct-current motors range in size from 0.5 to 20 horse power and aggregate about 500 horse power. There are also induction motors operating from the lighting circuits, ranging in size from one to

75 horse power, and aggregating about 300 horse power. The total peak supplied to the San José sub-station is about 1000 kilowatts.

The San Mateo division is operated from the sub-station at Redwood. Distribution is made at 6000 volts, two-phase, to

FIG. 5.

neighboring small towns. Induction motors in this division range in size from one to thirty horse power, and aggregate about 500 horse power, constituting chiefly a day load. The maximum load supplied to the station occurs between the hours of five and nine p. m., giving a peak of about 400 kilowatts.

At the San Francisco sub-station, the low-tension circuits are Y-connected with the neutral grounded, and supply power at 4000 volts between lines to station B, and to station C of the San Francisco Gas and Electric Company. At station C are two 500-kw. synchronous motor-generator sets, and at station B there is one 400-kw. synchronous motor-generator set. Station B also contains two 1200-kw. and one 600-kw. G. E. revolving-field generators, one or more of which were operated in parallel during these tests with the Standard system, being thrown in at about 5 30 p. m. and off at about 10 30 p. m. The peak was about 2000 kilowatts. These were the conditions during the tests. Since the consolidation of the Standard and Bay Counties systems, the above description does not hold.

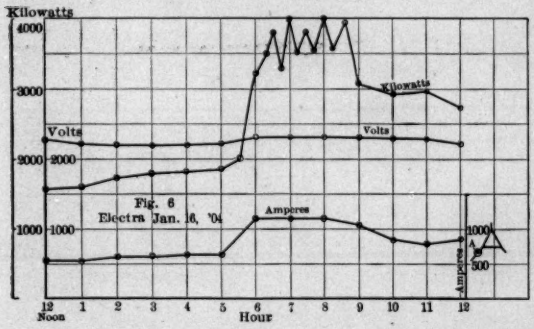


Fig. 6
Electra Jan. 16, '04

The instrument with which the following tests were made was the well known Blondel oscillograph. Briefly, it consists of two thin strips of soft iron stretched vertically between the poles of a powerful permanent magnet. Very small mirrors are attached to these strips, and each strip and mirror is placed in a tube containing glycerine or vaseline oil. The natural frequency of the instrument as given by the maker is about 1000 cycles per sec. About each of the mirrors as centers, two bobbins or coils serve to produce fields, one proportional to the current, and the other proportional to the electromotive force. The current coil required about 10 amperes to produce a convenient deflection on the plate, and the electromotive force about 0.333 ampere. A diagram through a vertical section of the instrument is shown

in Fig. 7. Light from the arc A passes through the slits S, through the small lens L in the oil tube to the mirror M, then through the cylindrical lens C to the vibrating mirror V and thence to the ground-glass screen or photographic plate $D\,G$. The mirror V vibrates so as to produce motion of translation of the point of light from D to G, the vibration being produced by the cam K operated by means of a small synchronous motor P. The apparatus is equipped with an electrical shutter which cuts off the return curve from G to D and further allows the taking of photographs.

The apparatus was connected in the following tests as in Fig. 8. A non-inductive resistance R consisting of incandescent lamps was placed in series with the pressure coil, and the current coil was shunted across the non-inductive resistance R' through the series resistance R''.

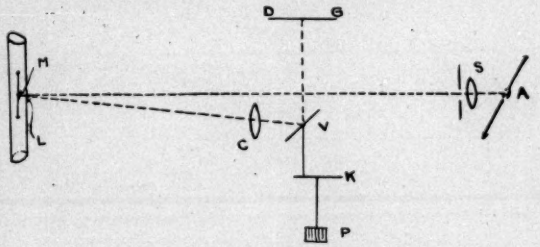


FIG. 7.

This apparatus was tried on generators of known wave form, on non-inductive loads, on leading and lagging currents supplied to a synchronous converter, and found to give consistent results.

During November 1903, a large number of observations was made at Stanford University of the electromotive force waves from the lines of the Standard company, which supplies the university with light and power. It soon became apparent that the wave form varied considerably, the distortion varying apparently with the time of day, and hence probably with the load.

On Saturday November 28th, negatives were made at approximately 30-minute intervals, beginning at 3 00 p. m. and ending at 12 30 a. m. on Nov. 29th. Tracings of these waves are shown in Fig. 3, the time of taking being given at the left of

each curve. They were taken across the terminals of one of two transformers arranged to supply a 120-volt, two-phase synchronous converter, the synchronous converter being disconnected. The electromotive force varied between the limits of 88 and 103 volts during the test. Counting from the power-house, this pressure was the result of four transformations; namely, from the generator at 2200 volts to 36 000 volts at Electra; from 36 000 to 6000 volts at Redwood sub-station, and also a phase transformation from three-phase to two-phase;

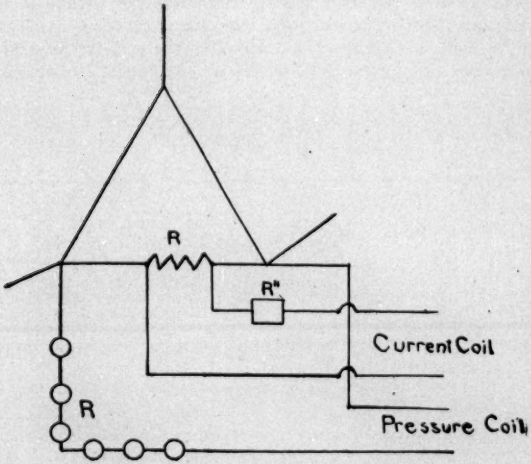


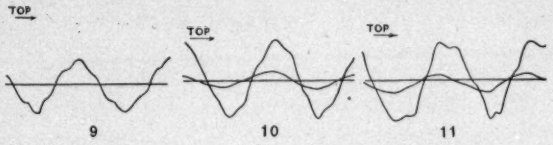
FIG. 8.

from 6000 volts to 2300 at Stanford power-house; and from 2300 volts to 90 volts in the transformer from which readings were taken. The original curve taken at 7 15 p. m. is reproduced in Fig. 9. This curve was enlarged photographically, so that the length of one cycle was 2π inches when its equation was found to be

$$y = 1.718 \sin (\theta - 0^\circ\ 20') + 0.063 \sin (3\theta + 177^\circ\ 31') + 0.138 \sin (5\theta - 29^\circ\ 15') + 0.028 (7\theta - 90^\circ) + 0.001 \sin (9\theta - 90^\circ)$$

The positive and negative halves of the wave are not quite the same, due probably to a slight pumping of the synchronous motor operating the vibrating mirror. The above equation represents two half-waves similar to the positive half-wave. It will be noticed that the 12 30 wave approaches sine-wave form.

On Thursday December 31st 1903, the waves represented in Fig. 2 were taken at San José. The pressure coil of the instrument was placed across the 2300-volt mains through lamps in series, and the current coil was shunted across a non-inductive resistance placed inside the $\triangle$. The distortion first appeared at 4 36, when the lighting load began to come on, the day being dark and rainy. This curve together with one taken at 7 28 are reproduced in Figs. 10 and 11. The wave taken at 7 28 was enlarged so that one wave length was 2π inches in length,



and analyzed graphically, for the first three harmonics. The equation is as follows:

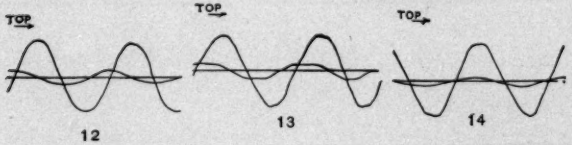
$$y = 2.89 \sin (\theta - 17') + .0283 \sin (3\theta + 56^{\circ}\ 58') + 0.22 \sin (5\theta + 180^{\circ}\ 6')$$

The small motor operating the mirror pumped badly. The above equation shows a 9.7% third harmonic and a 7.6% fifth harmonic. Since synchronous-motor load predominated, the current leads by a small angle.

On Saturday January 16th 1904, the curves shown in Fig. 1 were taken at Electra. The connections were the same as those at San José, the electromotive force being taken across the 2300-volt mains and the current being shunted across a non-inductive resistance inside the $\triangle$. The pressure waves show little variation throughout the night. From 2 45 p. m. until 12 00 midnight two generators were in parallel. At 2 10 p. m. and at 2 00 a. m. are shown the wave forms of a single generator. The original curves taken at 2 10 p. m. when the load was light, and at 7 41 p. m. when the peak occurred, are shown in Figs.

12 and 13. Large leading current is shown in both. The average output at the peak is 3700-kw., the line current 1150 amperes and the pressure 2280 volts. The power-factor by switchboard instruments would therefore be 80%, indicating a lead of 37 degrees. The curve, Fig. 13, shows greater lead than this. The calculated charging current for the Bay Circuit is about 30.3 amperes on the assumption of a sine wave with a corresponding generator current of 500 amperes. The line current at 2 10 p. m. was 550 amperes. The power-factors figured from the curves and from instrument readings do not agree. The curves show a gradual change in lead angle from 2 10 to 7 41 while the wattmeters indicate only a small change in power-factor. The wattmeters probably do not indicate correctly on the very large leading current.

In Fig. 14 are shown the waves of electromotive force and current supplying the mining circuits at 17 000 volts, the lagging induction-motor load neutralizing the charging current.



The curves reproduced in Fig. 4 were taken at the San Francisco sub-station on Feb. 6th. The transformers, as before stated, are here Y-connected to the 4000-volt mains of the San Francisco Gas and Electric Company. The pressure coil was connected between the neutral and one line, the current coil being shunted across a non-inductive resistance as in the preceding cases. The original curve reproduced in Fig. 15 was taken at 7 40 p. m. The last wave taken at 1 30 is seen to be practically the generator wave as shown at 2 10, Fig. 1. Although these observations were not taken simultaneously, load conditions were probably nearly the same for all of the four sets. The load curves also were much the same as those plotted for Jan. 16th.

Figs. 2 and 4 are seen to be similar. Had a fourth set been taken at Redwood from the three-phase circuit, it would have been probably similar to 2 and 4. Pressures corresponding to

the waves as given in Figs. 1, 2, 3, and 4 are given in the following table:

Electra.	San José.	Stanford.	San Francisco.
2200	2200	98	2500
2200	2240	96	2500
2200	2240	103	2500
2200	2220	95	2500
2200	2220	92.5	2500
2200	2300	90	2520
2200	2340	88.5	2600
2300	2300	89	2600
2300	2300	89	2600
2300	2300	89	2600
2300	2320	90.5	2600
2280	2340	90	2590
2280	2320	95	2500
2280	2300	96	2500
2280	2220	94	2500
2280			
2280			
2280			
2200			
2200			
2200			

While taking observations at San José, there was considerable pulsation on the line, especially at 6 38, due to the generators of the San Francisco Gas and Electric Co. which were operating in parallel. The effect as observed on the ground-glass screen of the instrument was a see-sawing of the two peaks of the wave: when the amplitude of one increased, that of the other diminished, and the reverse. This phenomenon suggested that perhaps the distortion was entirely due to the influence of the San Francisco generators This assumption is, however, not borne out by Fig. 16 taken at San Francisco with the generators disconnected. The wave form of the San Francisco generators is shown in Fig. 17. A moving film attachment to the instrument would give much valuable information on surging caused by switching, short circuits, or pulsations due to any cause.

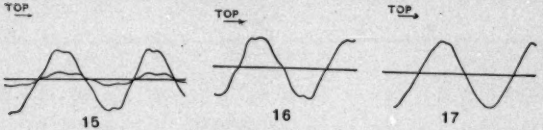
The effect of the variable wave form in low-tension circuits as shown in Fig. 3 on the accuracy of an induction meter was investigated and found to be negligible. It is, however, probable that the accuracy would be considerably affected on wave forms like those shown in Figs. 2 and 4, depending on the amplitude and phase relations of the harmonics.

The variation of the core losses has not yet been determined. The ratio of maximum to virtual in curve 7 28, San José, is 1.4,

and the ratio in curve taken at 11 p. m. is 1.55, indicating a 10% variation and therefore, an inverse variation in core loss. Maximum pressures as derived either from spark determination or from transformer ratio may also be considerably in error.

There is reason to believe that greater variations occur on long lines which are more fully loaded. The large wattless currents sometimes observed in synchronous motors and synchronous converters with fields adjusted for minimum current are probably due to wave-form differences. These together with pulsation difficulties could be satisfactorily observed with a moving-film oscillograph.

Where so many disturbing elements are present it is difficult to select the predominating cause of distortion. Doubtless it is due to the influence of synchronous motors of dissimilar wave form, to alternators of dissimilar wave form, and largely to the



15 16 17

pulsation of reactance. Mr. Pikler* has shown that when a generator gives sine wave form, variation of resistance interposed between generator and transformer, the latter working on normal voltage, produces distortion of wave form in the transformer secondary. Similarly figures 1, 2, 4 and 6, show that with sine wave form at the generator, distortion in the 2300-volt secondary varies with the line drop.

The following summary of conclusions is suggested for consideration:

1. Advisability of substituting induction motors for synchronous motors on lines with large charging current, and the use of the latter as synchronous compensators properly distributed.

2. The impossibility of designing machines to suit all wave forms.

3. The oscillograph offers the best means of studying variations in wave form, amplitude factor, surgings, pumping, etc.

* See *Elec. World*, Aug. 8, 1903.

4. The best form of oscillograph for this work is the moving-film or falling-plate type, without the synchronous motor attachment. It should be insulated for use on high pressures, and fitted with non-inductive metallic resistances.

5. The variation in amplitude factor in a long line may be considerable.

6. Core-loss variation may also be considerable.

7. The charging current may differ from that calculated on the assumption of a sine law.

8. Assumption of sine-wave form on long lines and applied to insulator and insulation testing may lead to error.

9. Variation of wave form partly due to distorting effect of hysteresis loop under different conditions of load.

The writer wishes to acknowledge the courtesy of Professor J. N. LeConte in allowing the use of his harmonic analyser, and for valuable assistance in its use. The writer also wishes to acknowledge the assistance of Mr. Joseph Mini, Jr., whose experience in high-pressure work rendered his services particularly efficient.

Appendix.

In an article by the writer on Wave Form Variations, the prediction was made that the core losses in apparatus operated from the lines of the Standard System would vary 10% under normal conditions of operation due to change in form factor of the electromotive force wave.

To verify this statement the following tests were made, June 17, 1904, on a 300-kw. Stanley transformer. Pressure from the standard line was applied at 2300 volts to the transformer through an induction regulator, by means of which the pressure was maintained constant. The core loss was measured by means of a Weston wattmeter supplied with a non-inductive multiplier. The speed of a synchronous motor running light was used to determine any variation of the frequency. Pressure was applied to the transformer 24 hours before taking observations, water being allowed to flow through the cooling coils until temperature conditions were constant.

The following readings were taken:

Time	Volts	Speed	Temp. fahr.	Kilowatts
9 00	2300	518	94	5.92
9 35	2300	519	94	5.92
10 05	2300	518	94	5.92
10 35	2300	520	94	5.72
11 00	2300	519	94	5.72
11 30	2300	519	94	5.92
11 55	2300	520	95	6.02
12 55	2300	518	96	6.12
1 25	2300	520	96	5.92
1 55	2300	520	96	6.12
2 25	2300	519	97	6.12
3 00	2300	520	97	6.12
3 30	2300	518	98	6.12
4 00	2300	519	98	6.12
4 30	2300	519	98	6.32
4 55	2300	519	98	6.12
5 30	2300	520	98	6.12
6 05	2300	520	98	6.12
6 30	2300	520	98	6.12
7 00	2300	520	98	6.12
7 30	2300	520	98	6.12
8 00	2300	520	98	6.02
8 30	2300	520	98	5.92
9 00	2300	520	99	5.92
9 30	2300	520	102	6.00
10 00	2300	520	100	6.02

APPENDIX.

Time	Volts	Speed	Temp. fahr.	Kilowatts
10 30	2300	520	100	5.92
11 00	2300	520	99	5.96
11 30	2300	520	100	5.94
1 00	2300	520	98	5.9
2 00	2300	515	96	5.82
3 00	2300	518	94	5.9
4 00	2300	519	94	5.72
5 00	2300	519	93	5.72
6 00	2300	519	92	5.82
6 30	2300	518	92	5.9
7 00	2300	519	94	5.87
7 30	2300	520	94	5.9
8 00	2300	520	94	5.92
8 30	2300	519	93	5.92
9 00	2300	520	93	5.72

The results show a total variation in core loss of 10% of the mean value. If correction is made for the variation of temperature on the assumption of 8% variation in core loss for 40° fahr. variation in temperature, the variation due to variable wave form is increased to 10.8%. The variation in speed is insignificant.

[For discussion on this paper, see page 469.]

BLANK
PAGE

A paper presented at the 187th Meeting of the American Institute of Electrical Engineers, New York, May 17-18, 1904.
Copyright 1904. By A. I. E. E.

DATA AND TESTS ON A 10 000 CYCLE-PER-SECOND ALTERNATOR.

BY B. G. LAMME.

In the early part of 1902, M. Leblanc, the eminent French engineer, was in this country, and spent considerable time at the Westinghouse Electric & Manufacturing Company's work at East Pittsburg. M. Leblanc was very much interested in certain special telephone work, and in connection with such work he desired for experimentation a current of very high frequency. He took up with the writer the question of building a successful alternator for generating current at frequencies between 5000 and 10 000 cycles per second. He was informed that the machine would necessarily be of very special construction, but that it was not an impossible machine. Later he took up the matter with Mr. Westinghouse, who, upon receiving satisfactory assurance that such a machine was possible, advised that the generator be built. A preliminary description of the general design was given M. Leblanc before he returned to Paris. He was somewhat surprised at certain of the features proposed, especially at the fact that an iron-cored armature was considered feasible for a frequency of 10 000 cycles per second.

The machine was designed and built on practically the lines of the preliminary description furnished M. Leblanc. The frequency being so abnormal, the writer believes that many features in the machine, with the results obtained, will be of scientific interest, and therefore the data of the machine, and the tests obtained are presented herewith.

The starting point in this machine was the sheet-steel to be used in the armature. No direct data were at hand showing losses in sheet-steel at such high frequencies, nor was there at

hand any suitable apparatus for determining such losses. As preliminary data, tests at frequencies up to about 140 cycles per second were used, and results plotted in the form of curves; these results were plotted for different thicknesses of sheet-steel. Also, tests were obtained showing the relative losses due to eddy currents and hysteresis, and these were plotted, taking into account the thickness of the sheets. These data were not consistent throughout; but the general shape of the curves was indicated, and in this way the probable loss at the frequency of 10 000 cycles per second was estimated for the thinnest sheet-steel which could be obtained. The steel finally obtained for this machine was in the form of a ribbon about 2 in. wide, and about 0.003 in. thick, which was very much thinner than any steel used in commercial dynamos or transformers, which

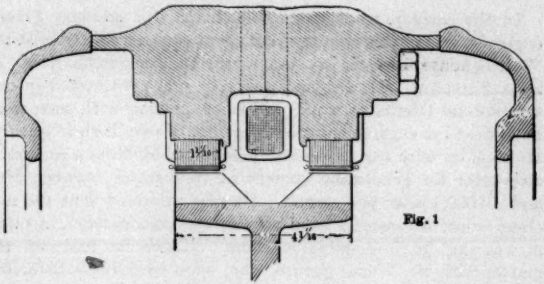


Fig. 1

varies from 0.125 to 0.0280 inch. Therefore the machine had to be designed with the intention of using this narrow ribbon of steel for the armature segments.

A second consideration of great importance in the construction of such a machine is the number of poles permissible for good mechanical construction. For instance, at 3000 revolutions—which was adopted as normal speed—the number of poles required is 400 for 10 000 cycles per second. The frequency, expressed in terms of alternations per minute, multiplied by the pole-pitch in inches, gives the peripheral speed in inches. At 1 200 000 alternations per minute (or 10 000 cycles per second) and a pole pitch of 0.25 in., for example, the peripheral speed of the field will be 25 000 feet per minute. It was therefore evident that either a pole construction should be

adopted which would stand this high peripheral speed, or the pole-pitch should be less than 0.25 in. It was finally decided that an inductor type of alternator would be the most convenient construction for this high frequency; with the inductor type alternate poles could be omitted, thus allowing 200 pole projections, instead of 400. The field winding could also be made stationary instead of rotating, which is important for such a high speed. This construction required a somewhat larger machine for a given output than if the usual rotating type of machine were adopted; but in a machine of this type where everything was special the weight of material was of comparatively little importance, and no attempts were made to cut the weight or cost of the machine down to the lowest possible limits.

The following covers a general description of the electrical and magnetic features of the machine:

Armature.—The armature was built up in two laminated rings dovetailed into a cast-iron yoke, as indicated in Fig. 1.

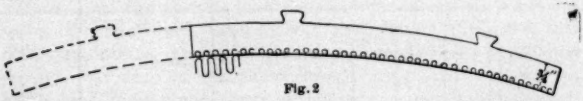


Fig. 2

The laminations were made in the form of segments dovetailed to the cast-iron yoke (Fig. 2). Special care was taken that the laminations made good contact with the cast-iron yoke, as the magnetic circuit is completed through the yoke.

The armature sheet-steel consisted of plates of 0.003 in. thickness. The sheet-steel was not annealed after being received from the manufacturer; it was so thin that to attempt annealing was considered inadvisable. To avoid eddy currents between plates each segment was coated with a thin paint of good insulating quality. This painting was a feature requiring considerable care and investigation, as it was necessary to obtain a paint or varnish which was very thin, and which would adhere properly to the unannealed laminations. These laminations had a bright polished appearance quite different from that of ordinary steel. They were so thin that the ordinary paint or varnish used on sheet-steel made a relatively thick coating, possibly almost as thick as the plates themselves. A very thin varnish was finally obtained which gave a much thinner coating than the plate itself, so that a relatively small part of the armature space was taken up by the insulation between plates.

Each armature ring or crown has 400 slots. Each slot is circular and 0.0625 inch diameter (Fig. 3). There is 0.03125 inch opening at the top of the slot into the air-gap, and the thickness of the overhanging tip at the thinnest point is 0.03125 inch.

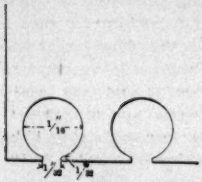


Fig. 3

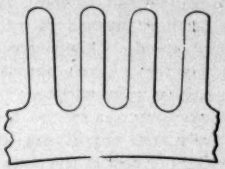


Fig. 5

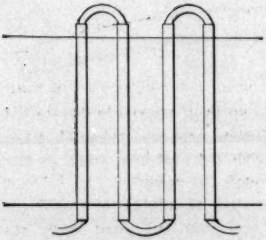


Fig. 4

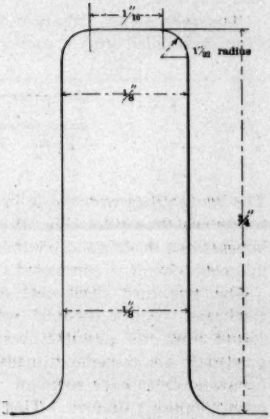


Fig. 6

The armature winding consists of No. 22 wire, B & S gauge, and there is one wire per slot. The entire winding is connected in series (Fig. 4). The measured resistance of the winding is 1.84 ohms at 25° cent.

After the sheet-steel was built up in the frame, it was ground out carefully. The laminations were then removed, all burred edges taken off and the laminations again built up in the frame. The object of this was to remove all chances of eddy currents

between the plates due to any filing or grinding. The finished bore of the armature is 25.0625 inch.

Field or Inductor.—This was made of a forged-steel disc 25 in. diameter turned into the proper shape, and the poles were formed on the outside by slotting the periphery of the ring. The general construction is indicated in Figs. 1 and 5. The poles were 0.125 in. wide and about 0.75 in. long radially and were round at the pole-face. Fig. 6 shows the general dimensions of a pole.

The field winding consisted of No. 21 wire, B. & S. gauge. There were 600 turns total arranged in 30 layers of 20 turns per layer. The field coil after being wound was attached to a light brass supporting ring. The general arrangement of the field or inductor, armature yoke, and bearings, is as indicated in Fig. 1. The measured resistance of the field winding is 53.8 ohms at 25° cent.

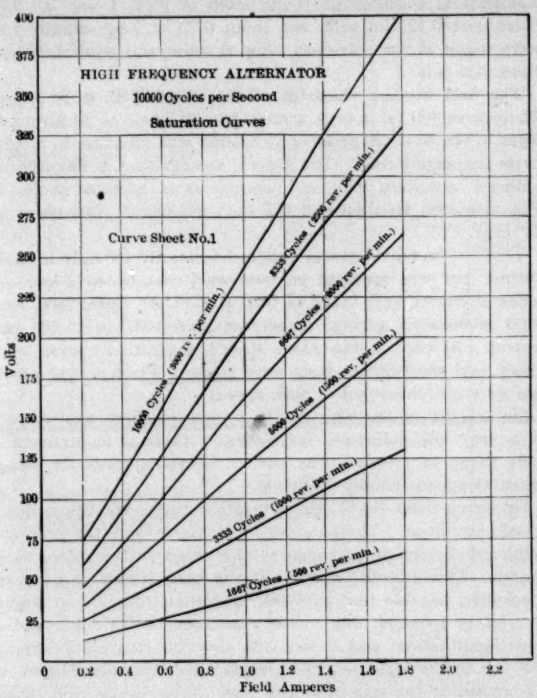
Tests.—The machine was designed primarily for only a small output, but was operated on temporary test up to 2 kw. A series of curves were taken at 500, 1000, 1500, 2000, 2500, and 3000 revolutions, giving frequencies from 1667 to 10 000 per second. At each of the above speeds, saturation curves, iron losses, and short-circuit tests were made. Friction and windage were also measured at each speed.

On account of the high frequency, the machine was worked at a very low induction; consequently there is an extremely wide range in pressure, the normal operating pressure being taken at approximately 150 volts.

On curve sheet No. 1, the saturation curves for the various speeds are given. These curves check fairly well, the pressure being practically proportional to the speed with a given field charge. This is to be expected at the lower speeds, but it was considered possible that at 3000 revolutions the air-gap might be slightly lessened, due to the expansion of the rotor under centrifugal action; and it was also thought that eddy-current loss due to the high frequency might affect the distribution of magnetism at the armature face; but the armature iron losses were comparatively small, and there appeared to be no such effect. Also there appears to be no effect due to expansion at high speed. The air-gap specified for this machine is 0.03125 in. on each side or 0.0625 in. total gap. A very small variation in the diameter of the inductor or the bore of the armature would make a relatively large per cent. in the effective air-gap.

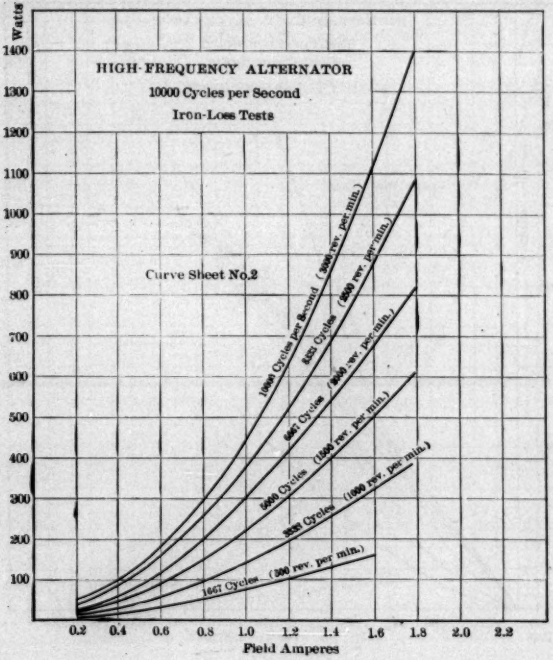
Therefore no reliable calculations can be made on the saturation curves of this machine based upon the specified air-gap.

Curve sheet No. 2 shows the iron losses at various speeds from 500 to 3000 rev. per min.—1667 to 10 000 cycles per second. These losses are plotted in terms of watts for a given exciting



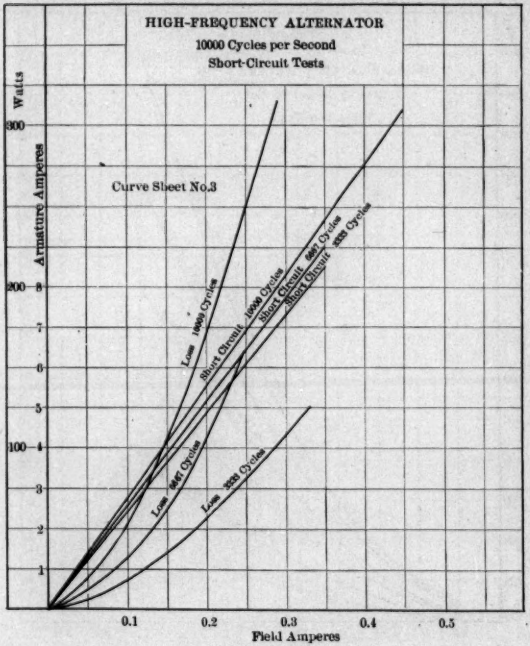
current. These curves show a rather unexpected condition as regards the losses. According to the original data showing the relative losses due to eddy currents and hysteresis, the eddy-current loss even with these thin plates should have been much higher than the hysteresis loss, but these iron-loss curves show

losses with a given field charge almost proportional to the frequency, which is the ratio that the hysteresis loss alone should show. As the eddy-current loss varies as the square of the frequency, the writer expected this to be a large element in the total iron loss, especially at the higher inductions. The six curves shown on this test-sheet are fairly consistent



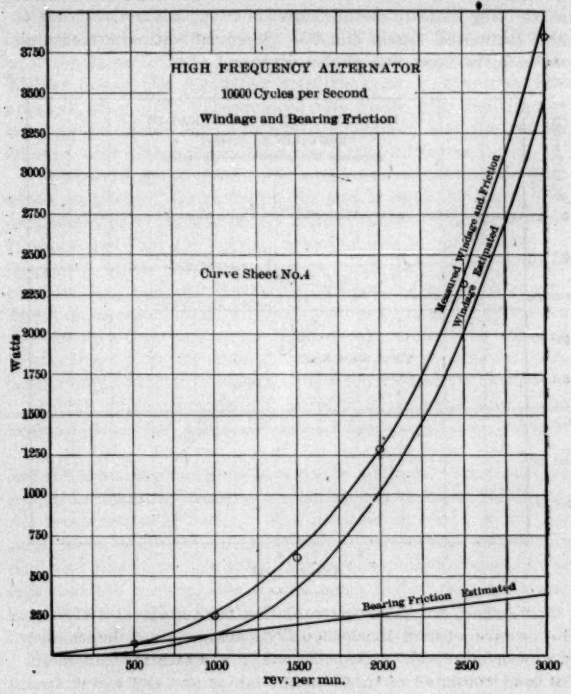
with each other, but it should be remembered that in making measurements of such abnormal apparatus little discrepancies in the curves could easily creep in. For instance, in the saturation curve a series of experiments were first made to find whether usual types of voltmeters were satisfactory, and a num-

ber of different methods for checking these readings were used. In determining the iron losses in curve sheet No. 2, the machine was driven by a small motor and the losses measured with different field charges. Under most conditions of test the iron loss was a small element of the total loss, and therefore slight variations in the friction loss would apparently show large variations



in the iron losses. Also the fly-wheel capacity of the rotating part of the alternator was comparatively high. Therefore, if there are any variations in the circuits supplying the driving motor, there would tend to be considerable fluctuations in the power supplied. Considering all the conditions of test, the curves appear to be remarkably consistent.

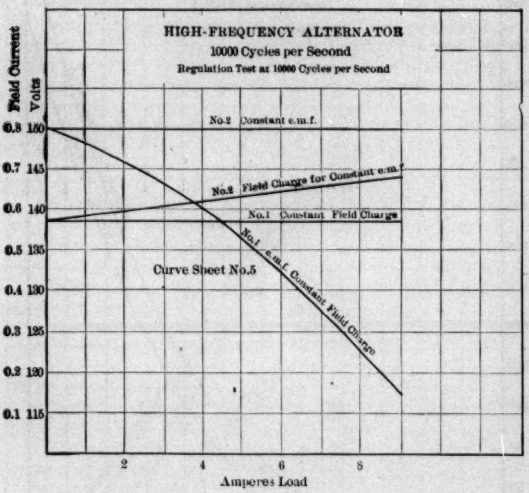
Curve sheet No. 3 shows the short-circuit curves at speeds of 1000, 2000, and 3000 rev. per min., or frequencies of 3333, 6667, and 10 000 cycles per second, respectively. It should be noted that at a given frequency the short-circuit current is proportional to the field current over the entire range measured,



but that the short-circuit current is not the same for the same field current at the various frequencies. According to these curves the current on short circuit increases somewhat with the given field charge as the frequency is increased.

Curve sheet No. 4 shows the measured windage and friction losses plotted at speeds from 500 to 3000 rev. per min. This

curve indicates clearly that the windage is the principal friction loss at the higher speeds. The writer has added two curves, one showing the estimated bearing friction loss, and the other the estimated windage, based upon the assumption that the bearing friction varies directly as the revolutions and the windage loss with the third power of the revolutions. The small circles lying close to the measured loss curve show the sum of these estimated losses, and the agreement with the measured loss is fairly close over the entire range.



Curve sheet No. 5 shows regulation tests made at 150 volts. The power-factor of the load on this test was not determined, as it was extremely difficult to make accurate measurements. The load consisted of incandescent lamps and the wiring from the machine to the lamps was non-inductive for the usual frequencies; but at the abnormal frequency of 10 000 cycles per second it is more difficult to obtain a true non-inductive load with ordinary apparatus. The tested regulation indicates that the load was practically non-inductive.

In first undertaking tests on this machine there was consid-

crable difficulty in measuring the pressures. It was found that at a frequency of 10 000 cycles per second the Weston voltmeter did not work satisfactorily. Practically the same deflection was obtained on the high and low scales of a 60-120 volt Weston alternating-current direct-current voltmeter with the same pressure.

Very good results were obtained by the use of a form of static voltmeter devised by Mr. Miles Walker. This voltmeter is of the same form as the static wattmeter described by Mr. Walker before the AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS, May, 1902.* Tests were also made with the Cardew hot-wire voltmeter with the high frequencies, and the results checked very satisfactorily with the static voltmeter.

For measuring the current a current dynamometer was used which had wood upright supports and a celluloid dial. The only metal parts outside of the copper coils were brass screws It was found that the current dynamometer is not affected by frequency, unless there are adjacent metal parts in which eddy currents can be generated which react upon the moving element. The dynamometer used had but a few turns in order to reduce the pressure drop across it. This dynamometer was checked very carefully at different frequencies and apparently gave similar results for any frequency between 25 and 10 000 cycles

Several temperature tests were made on this machine. The heaviest load on any test was 13.3 amperes at 150 volts, or 2-kw. output. This test was of two hours' duration, and at the end the armature iron showed a rise of 16° cent.; the armature copper 21° cent. by resistance, and the field copper 17.3° cent. Air temperature 19° cent. The machine showed a relatively small increase in temperature at this load over the temperature rise with one-third this load. This was probably due to the fact that the windage loss was so much higher than the other losses of the machine that the temperature was but little affected by the small additional loss with increase in load.

Attempts were made to utilize the current from this machine for various experiments, but difficulty was at once found in transforming it. At this high frequency no suitable iron-cored transformer was available. Transformers with open magnetic circuits were tried and operated better than those with iron cores but were still rather unsatisfactory. It was decided that nothing could be done in this line without building special transformers.

[*TRANSACTIONS of the A. I. E. E., Vol. XIX, p. 1035.]

Among the few experiments made was that of forming an arc with current at this high frequency. This arc appeared to be like an ordinary arc so far as the light was concerned, but had a very high-pitched note corresponding to the high frequency. This note was very distressing to the ears.

This machine is in reality of the nature of a piece of laboratory apparatus; and at present it has no commercial value. It was designed primarily for scientific investigation, and appears to be a very good machine for that purpose.

[For discussion on this paper, see page 459.]

A paper presented at the 187th Meeting of the American Institute of Electrical Engineers, New York, May 17-18, 1904.
Copyright 1904, by A. I. E. E.

THE SINGLE-PHASE INDUCTION MOTOR.

BY WILLIAM S. FRANKLIN

Fig.1 represents a rotor having $2Z$ conductors, surrounded by a stator having a two-pole winding of N conductors spread over two opposite arcs each of 90° span. Each rotor conductor is supposed to be short-circuited through the conductor lying opposite to it so that the rotor presents Z independent circuits each of resistance R. In case the rotor conductors are short-circuited by end-rings, as in the squirrel-cage rotor, it is an easy matter, knowing the resistance of each rotor conductor and the resistance per unit length of the short-circuiting ring, to calculate the value of R for an equivalent winding of the type here specified.[1]

This rotor whether standing or running is magnetically stationary and magnetically equivalent to a rotor such as shown in Fig. 2 having a concentrated winding $A\,A'$ of $\frac{Z}{4}$ turns each of resistance R, and a concentrated winding $B\,B'$ of $\frac{Z}{4}$ turns each of resistance R*.

Consider an alternating flux, Φ, Fig. 2, stationary in space but harmonically distributed around the periphery of the rotor as it flows into the rotor from the stator, or into the stator from the rotor. Let E_0 be the pressure induced in the $2N$ conductors

1. In fact R is equal to the resistance of two conductors of a squirrel-cage winding plus $\frac{2z}{\pi}$ times the resistance of an arc of one of the short-circuiting rings of which the length is equal to the diameter of the ring.

*This result is reached by integrating the magnetomotive force of $Z/2$ independent phases of alternating current around the periphery of the motor.

(N turns) of the stator winding by this alternating flux and E_1, the pressure which this flux induces in the Z conductors (Z) turns of the rotor winding B. Then $E_o/E_1 = 0.901 \times N/Z/2 = 1.802 \times N/Z$, 0.901 being the ratio of the chord to the arc of 90°†. Therefore to give a 1:1 ratio of transformation between stator winding and rotor winding B; that is, to make $E_o = E_1$, we may change the stator winding to give $N = Z \div 1.802$. Along with this change of N we may imagine

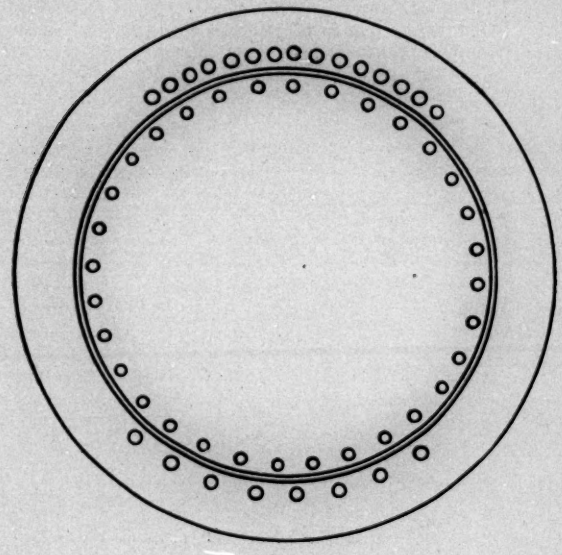


FIG 1.

the value of the supply pressure to be changed in the same ratio, and the sectional area of the wire used in the stator winding to be changed in the inverse ratio. In this way any given single-phase motor with any type of rotor and having a stator winding of any number of turns spread over any arc may be reduced to the equivalent 1:1 arrangement, and there-

†. See Franklin and Williamson, pages 121 to 123.

fore the following theory is worked out for this 1:1 arrangement.

It is to be noted that the flux Φ, Fig. 2, which is stationary in space but alternating at a given frequency f induces the same pressure in any winding (distributed or concentrated) as would be induced in the same winding by a flux having a constant value equal to the maximum value of Φ but rotating at a speed equal to the frequency f, provided that the flux is in each case harmonically distributed around the periphery of the rotor.

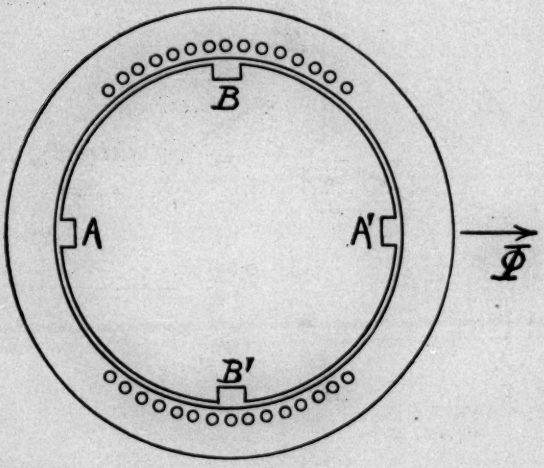


FIG. 2.

The special use to be made of this fact later is that, from it, we know that the pressure induced in the B winding by pulsations of Φ is to the pressure induced in the A winding by the turning of the rotor through Φ, as the frequency of pulsation of Φ is to the speed of rotation of the rotor.

It is furthermore to be noted that the windings A and B, Fig. 2, which represent magnetically the actual rotating windings of the rotor, are stationary, and therefore all electromotive forces induced in rotor windings and all rotor currents are to be

considered to have the same frequency as the electromotive force applied to the stator windings.[1]

Fig. 3 represents diagramatically the stator winding of a single-phase induction motor and the two stationary windings A and B which represent the moving rotor windings at each instant. When a periodic pressure E_0 acts upon any electromagnetic system the electric and magnetic effects produced are of the same periodicity. The most completely general periodic flux through the rotor Fig. 3 consists of two periodic fluxes Φ

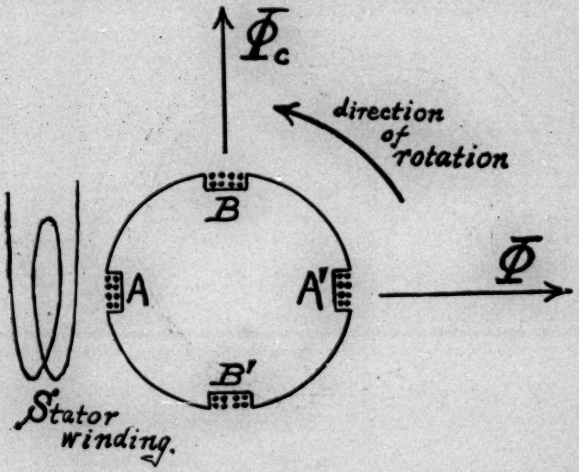


FIG. 2.

and Φ_0 perpendicular to each other in space and of which the phase difference in time may be anything whatever. We assume these periodic fluxes Φ and Φ_0 to be harmonic, and we shall develop the theory of the single-phase induction motor upon these fluxes as a basis. We shall call a pressure which is induced by the time variation of a flux a *pulsational pressure*, and a pressure which is produced by the cutting of flux by motion a *rotational pressure*.

1. See Franklin and Williamson, pages 244 and 245.

Notation.

E' = primary impressed pressure.

E_0 = part of primary pressure which is over and above the part used to overcome primary resistance R' and primary magnetic leakage reactance x.*

f = primary frequency

n = rotor speed

M = magnetizing current in primary

I_0 = load current in primary

I_1 = current in rotor winding A

I_2 = current in rotor winding B

R = total resistance of winding A and of winding B

$Z/2$ = turns in winding A and turns in winding B

N = turns in primary winding

The two fundamental equations of the single-phase induction motor express the following two conditions:

(a) That the sum of rotational pressure in A due to Φ and pulsational pressure in A due to Φ_0 shall be equal to $R I_1$, and:

(b) That the sum of the rotational pressure in B due to Φ_0 and the pulsational pressure in B due to Φ shall be equal to $R I_2$.

In considering these pulsational pressures and rotational pressures in A and B careful attention must be given to the matter of algebraic signs.

The positive directions of Φ and Φ_0 are chosen as represented by the arrows in Fig. 3 and the positive directions around windings A and B are chosen as customary in relation to the positive directions of Φ and Φ_0; that is, the positive direction around A is the direction in which a right-handed screw co-axial with Φ_0 would have to be turned to travel in the positive direction of Φ_0 and the positive direction around B is the direction in which a right-handed screw co-axial with Φ would have to be turned to travel in the positive direction of Φ. Therefore the positive direction around A is up A and down A', and the positive direction around B is up B and down B'.

With this choice of signs the pulsational pressure in A due to Φ_0 is equal to $2\pi f \frac{Z}{2} \Phi_0 / \sqrt{2}$ where Φ_0 represents the maximum value of the cross-flux, and this pulsational pressure is

*When the magnetizing current of a transformer is small compared with load current, primary and secondary currents are nearly in phase and all magnetic leakage reactance, both primary and secondary, may be located in the primary. See Franklin and Williamson, page 176.

90° behind Φ_e in time phase. Therefore this pulsational pressure in A may be written

$$-j \cdot \frac{\pi f Z \Phi_e}{\sqrt{2}}$$

Similarly the pulsational pressure in B due to Φ is

$$-j \cdot \frac{\pi f Z \Phi}{\sqrt{2}}$$

The rotational pressure in A due to Φ is in phase with Φ and positive when Φ is positive. It is therefore equal to

$$+ \frac{2 \pi n \frac{Z}{2} \Phi}{\sqrt{2}} \text{ or to } + \frac{\pi n Z \Phi}{\sqrt{2}}$$

The rotational pressure in B due to Φ_e is in phase with Φ_e and negative when Φ_e is positive. Therefore it is equal to

$$- \frac{\pi n Z \Phi_e}{\sqrt{2}}$$

Therefore we have the fundamental equations:

$$R I_1 = + \frac{\pi n Z \Phi}{\sqrt{2}} - j \cdot \frac{\pi f Z \Phi_e}{\sqrt{2}} \qquad (1)$$

$$R I_2 = - \frac{\pi n Z \Phi_e}{\sqrt{2}} - j \cdot \frac{\pi f Z \Phi}{\sqrt{2}} \qquad (2)$$

It is desirable to transform these two fundamental equations so as to eliminate the two quantities Φ and Φ_e. To this end we may write $k I_1$ for $\frac{\pi Z \Phi_e}{\sqrt{2}}$ where k is a constant. This is evident when we consider that the flux Φ_e is produced by the current I_1. Furthermore we may write E_o for $j \cdot \frac{\pi f Z \Phi}{\sqrt{2}}$ inasmuch as the pulsational pressure in B is opposite to E_o in phase, and equal to E_o if we make N equal to $Z/1.802$. Therefore equations (1) and (2) become

$$R I_1 = -j \cdot \frac{n E_0}{f} - j k f I_1 \qquad (3)$$

$$R I_2 = -k n I_1 - E_0 \qquad (4)$$

Now I_1 is wholly a magnetizing current and it is therefore comparatively small in value so that as a first approximation $R I_1$ may be placed equal to zero. The effect of $R I_1$ upon the performance of the motor will be considered later. Therefore equation (3) becomes:

$$o = n E_0 + k f^2 I_1 \qquad (5)$$

or

$$I_1 = -\frac{n E_0}{k f^2} \qquad (6)$$

Substituting this value of I_1 in equation (4) and solving for I_2 we have:

$$I_2 = \frac{E_0}{\left(\frac{f^2}{n^2 - f^2}\right) R} \qquad (7)$$

or, since $I_0 = -I_2$ we have

$$I_0 = \frac{E_0}{\left(\frac{f^2}{f^2 - n^2}\right) R} \qquad (8)$$

which shows that the load current, I_0, in the primary may be thought of as being produced by the useful part E_0 of the primary pressure through a fictitious resistance $\left(\frac{f^2}{f^2 - n^2}\right) R$. This fact enables us to apply a modified form of the Heyland* diagram to the calculation of the performance curves of the single-phase induction motor.

Before proceeding to this application of the Heyland diagram it is interesting to consider the relation between Φ and Φ_0 on the assumption that $R I_1$ is equal to zero. Upon this assumption equation (1) reduces to:

$$o = n \Phi - j f \Phi_0 \qquad (9)$$

or

$$\Phi_0 = -j \cdot \frac{n}{f} \cdot \Phi \qquad (10)$$

*See Franklin and Williamson, page 256.

which shows that Φ_c is 90° behind Φ in time phase and that the ratio Φ_c/Φ is equal numerically to n/f. Therefore the cross-flux Φ_c is zero at standstill and it is equal to Φ at synchronous speed. Furthermore at standstill only the simple pulsating flux Φ passes through the rotor, as the rotor speeds up the re-

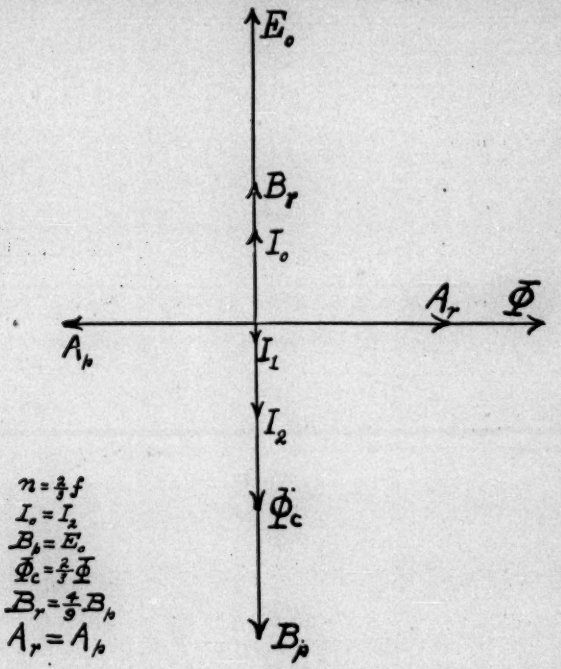


FIG. 4.

sultant flux through the rotor becomes an elliptically rotating flux, and when $n = f$ the resultant flux through the rotor be comes a rotating flux of unvarying value exactly as in the polyphase induction motor. Furthermore the magnetizing current I_1 being proportional to and in phase with Φ_c is 90°

behind Φ or 180° behind E_0 in time phase, it is equal to zero at standstill, and it increases in proportion to rotor speed, reaching at synchronism a value sensibly equal to the magnetizing current M in the primary winding.

The action of the single-phase induction motor running at speed n is as follows, magnetic leakage and primary resistance being ignored: the primary pressure acting on the primary winding produces a pulsating flux Φ, Fig. 3, which produces in the primary winding a pulsational pressure sufficient to balance the impressed pressure. This flux Φ produces in winding A, Fig. 3, a rotational pressure A_r, Fig. 4, which produces the magnetizing current I_1, which in turn produces the cross-flux Φ_c, and this cross-flux in its turn produces a pulsational pressure A_p in A which is equal and opposite to A_r, $R\,I_1$ being negligible. This cross-flux Φ_c produces a rotational pressure B_r in B which opposes the pulsational pressure B_p due to Φ but is considerably less in value so that the sum of B_r and B_p is an unbalanced pressure in phase with Φ_c and this unbalanced pressure produces a large current I_2 in B. The effect of this current I_2 is to permit the flow of an equal and opposite load-current I_0 in the primary coil by virtue of which the primary pressure delivers power to the motor. We shall now proceed to develop the equations of power and torque with the view of applying the Heyland diagram.

The total power delivered to the rotor is delivered to circuit B, Fig. 3, and it is equal to the product of I_2^2 into the fictitious resistance $\left(\frac{f^2}{f^2 - n^2}\right) R$. That is:

$$\text{Total power delivered to rotor} = I^2{}_2 R \left(\frac{f^2}{f^2 - n^2}\right) \quad (11)$$

Furthermore:

$$\text{Power lost in circuit } B \text{ as heat} = I_2^2 R \quad (12)$$

The difference between (11) and (12) is the power which is developed by the torque T which is exerted upon rotor circuit B. Therefore this difference must be equal to $2\pi n T$ so that

$$T = \frac{1}{2\pi} I_2^2 R \left(\frac{n}{f^2 - n^2}\right) \quad (13)$$

This is the equation which will be used in connection with the Heyland diagram, but a better idea of the relation between

torque and speed may be obtained by eliminating I_2^2 from (13) using equation (7). This gives:

$$T = \frac{1}{2\pi} \cdot \frac{E_0^2}{R} \cdot \left(\frac{n}{f^2} - \frac{n^3}{f^4} \right) \qquad (14)$$

Therefore, if there is no magnetic leakage so that E_0 may be considered as constant, the torque of a single-phase induction motor is proportional to $\left(n - \frac{n^3}{f^2} \right)$, and the torque is zero at standstill [$n = o$], and also at synchronous speed [$n = f$.]

The cross magnetizing current I_1 in so far as it represents loss of power gets its power from the revolving rotor through the action of a back torque, thus lessening the effective torque of the motor or with given motor load causing a slight decrease in speed and a corresponding slight increase in I_1 and in the primary load current I_0 which is in phase with E_0. The power loss represented by I_1 is partly $I_1^2 R$. The eddy current and hysteresis losses are distributed between the primary magnetizing current M and the cross magnetizing current I_1 approximately as follows: at standstill all the core loss is supplied by the power component of M and at standstill the core loss is large inasmuch as the rotor iron is then the seat of considerable loss. With increasing speed the total eddy current and hysteresis losses decrease and are shared between M and I_1, the part supplied by I_1 being proportional to the speed and equal to half the whole at synchronous speed. Therefore the power component of I_1 increases with increasing speed while the power component of M decreases with increasing speed, but the increase of power component of I_1 with speed means an increase of load current I_0 which supplies to the rotor the mechanical energy which is delivered to I_1 by back torque due to I_1, and one may think of this slight increase of I_0 as compensating the slight decrease of the power component of M so that it is permissible to consider the whole of the core losses as supplied by a constant or nearly constant primary magnetizing current, in which case the loss $I_1^2 R$ is the only loss to be associated with the cross magnetizing current I_1.

The cross magnetizing current I_1 in so far as it is wattless causes a slight pulsating increase and decrease of speed as it takes energy from and gives it back to the revolving rotor. If the moment of inertia of the rotor is large this pulsation of

speed is exceedingly small and in this case the wattless component of I_1 has no effect whatever upon the primary current. It is to be particularly noted that time lag of I_1 behind the rotational pressure due to Φ which produces I_1 does not involve any space lag so that the magnetomotive force due to I_1 has no component which opposes the flux Φ either when the resistance of winding A' is negligibly small or when the resistance of winding A is large. In other words the currents produced in the actual rotor windings by the rotational pressure due to Φ are always symmetrically distributed with respect to Φ (no space lag) although the maximum value of these currents may occur later than the instant at which $\frac{d\phi}{dt}$ is equal to zero. The idea of the carrying of the rotor currents around by the moving rotor out of the position in which they would be at standstill, thus creating a cross magnetomotive force, is entirely foreign to the fundamental idea of the magnetic representation of the rotor windings by the stationary windings $A\,A'$ and $B\,B'$; in fact the writer believes that this idea of the production of cross magnetomotive force by the carrying of rotor currents around out of opposition to the primary is essentially a wrong idea. The cross magnetizing current I_1 is produced through the mediation of a rotational pressure which is produced in the rotor conductors as they cut the flux Φ as above explained.

The wattless component of the primary magnetizing current represents a flow of energy from the source of supply to the magnetic field of the motor and back again, while the wattless component of I_1 represents a flow of energy from the kinetic store of the rotor to the magnetic field of the motor and back again. When a two-phase induction motor has one of its stator windings detached from the source of supply, thus becoming a single-phase motor, the wattless component of the magnetizing current in the remaining stator winding is unchanged in value, the power component of this magnetizing current is doubled, and the rotor, before rotating at constant speed, now rotates at a speed which rises and falls slightly at a frequency $2f$. This rise and fall of speed at zero load is due chiefly to the above-mentioned exchange of energy between rotor and cross-flux through the mediation of the wattless component of I_1, while under load the pulsations of speed are due not only to this cause but also to the fact that the load torque is steady while the driving torque, equation (13), pulsates between zero and $2\,T$.

The applicability of the Heyland diagram depends, as stated above, upon the fact that the flow of energy between the primary winding and the B winding of the rotor is identical to the flow of energy by ordinary transformer action from the primary winding to the B winding on the assumption that the B winding has its resistance increased to the fictitious value $\left(\frac{f^2}{f^2-n^2}\right)R$. The ratio of transformation being 1:1 the equivalent resistance of the primary circuit is $R'+\left(\frac{f^2}{f^2-n^2}\right)R$. This resistance varies with speed. The reactance x of the primary is equal to $2\pi f$

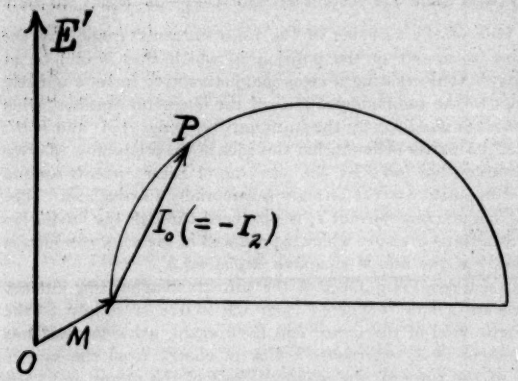


FIG. 5.

times the inductance value of magnetic leakage which may be easily calculated from the dimensions of the motor. This reactance is constant. Therefore the locus of I_0 is a circle of which the diameter is equal to E'/x and at right angles to E', and the locus of total primary current $M+I_0$ is the same circle with the origin displaced as shown in Fig. 5.

Having calculated M and x the diagram Fig. 5 is completely determined. To calculate a set of corresponding values of speed torque, etc., proceed as follows: choose any point P Fig. 5. This determines at once I_2, total primary current $M+I_0$, power-factor, and total power intake. Subtract from the power rep-

resented by the load current I_0 the resistance loss in the primary; namely, $(M+I_0)^2 R'$, and we have the total power delivered to the B circuit of the rotor. Thus from equation (11) the speed n may be calculated, I_2, R, and f being known. Knowing n, the total torque exerted on the B circuit may be calculated from equation (13) from which total torque the amount $I_1^2 R/2\pi n$ is to be subtracted, this being the back torque due to rotor circuit A. To calculate this back torque consider that I_1 is sensibly equal to the wattless component of the primary magnetizing current M. The total power output of the motor, ignoring friction, may now be calculated from speed and net torque. Then the efficiency may be calculated. Proceeding in this way for a series of points P Fig. 5 the data for plotting the complete performance curves of the motor may be obtained.

The author's thanks are due to Mr. S. S. Seyfert for a careful verification of the equations given in this paper.

[For discussion on this paper, see page 466.]

BLANK
PAGE

DISCUSSION ON "PREDETERMINATION OF SPARKING IN DIRECT-CURRENT MACHINES" AND ON THE "EFFECT OF SELF-INDUCTION ON RAILWAY-MOTOR COMMUTATION."

W. L. WATERS:—In the last two or three years the formula presented in this paper has been checked up on a complete line of machines which has been designed and built in sizes from 2 to 1000 kw. As indicated above, the allowable value of the sparking constant was found to vary with the number of poles, and the output and the type of winding on the armature; but among machines which were directly comparable in these respects the formula gave quite good results and usually the sparking limits of the machines could be predicted to within about 10 per cent.

Occasionally, however, we would come across machines, which gave results which varied quite considerably from those predicted by the formula. This variation being in some cases as much as 40 per cent. No apparent explanation of some of these variations was found and they were considered merely as evidences of the fact that this sparking formula does not by any means take into account all the conditions which affect the sparking, so that though the formula gives in general good results it should be used with a certain amount of discretion.

E. R. DOUGLAS:—Referring to Mr. Waters' paper, the speaker wishes to discuss, not the inequality factor, but the fundamental part of the formula which concerns the self-induction of the coil itself. On page 368 we read:

"The self-induction of one conductor embedded in the slot equals $l\,k$, where l is the length of the core and k is a constant depending on the dimensions of the slot."

On the next page is a curve, showing the relation between k and the proportions of the slot. This formula makes the self-induction of the coil depend entirely on the flux within the slot itself, neglecting a system of flux which is much more important in causing self-induction. Fig. 1 shows an armature of which but two slots, a and b, are drawn. A coil $c\,d$ lies in those slots. The current in that coil sets up a certain flux surrounding the conductors of the coil. A part of the flux, it is true, goes directly across the slots above the coil and through the wire itself, as $e\,f$. This is what Mr Waters has considered. But a further and larger portion of flux goes around in great sweeps g, which, if the armature were out of its magnet frame, would be uninterrupted to an indefinite distance. That portion of the inductance due to flux around the core may be greater than that due to flux within the slot. This was called to our attention in a paper entitled "Sparkless Reversal in Dynamos," by Mr. H. N. Allen, in the Journal of the British Institution of Electrical Engineers, in April, 1898.

Contrary to Mr. Waters' practice, Mr. Allen neglects the flux within the slot, but pays much attention to the flux around

the core. He assumes a very long drum armature, so that the ends do not come into consideration. In Fig. 2, let *a* and *b* represent cross-sections of two long parallel conductors carrying currents in opposite directions. The lines of magnetic flux surrounding these conductors will be represented by the lines *c*, and the equipotential surfaces of this magnetic flux by the lines *d*. The sections of flux and equipotential surfaces form two systems of circles cutting each other orthogonally. It is not difficult to compute the flux due to such a system.

If the space within any equipotential surface, as *d'*, be filled with material of perfect permeance, the values of the flux will be doubled in amount irrespective of which equipotential surface be chosen. Allen's formula is based on this conception, but is not satisfactory when applied to the ordinary type of

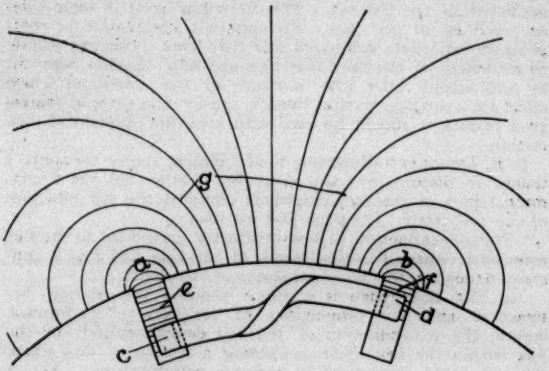


FIG. 1.

armature, because the ordinary armature is not a long cylinder, and the effect of the end connections is great.

A different conception was introduced in some work done by engineers of the Crocker-Wheeler Company. Instead of considering an infinitely long cylindrical core with two parallel conductors, a spherical core was assumed having a circular coil lying on it. Current circulating in the coil would set up a flux through the coil, spreading out in all directions.

The flux through a circular coil entirely surrounded by air is susceptible of calculation. If that coil be placed on a sphere of perfect permeability the flux will be increased, and it is also possible to calculate the increase. The flux around a circular coil on a spherical coil of high permeability may

therefore be known. Fig. 2 will also represent such a circular distribution, $a\,b$ being sections of the conductor of the circular coil, and $x\,y$ the axis. The surfaces of flux and of equipotential are very nearly spherical.

The ordinary armature coil has somewhat the shape of a regular hexagon. The inductance in air of a circular coil of the same enclosed area will not be very different from that of the hexagonal coil. The actual coil is laid on a core of high permeability; that core, it is true, is not spherical and does not touch the coil all around, but the inductance calculated for the circular coil and spherical core comes very near to the actual inductance. Of course it does not take into ac-

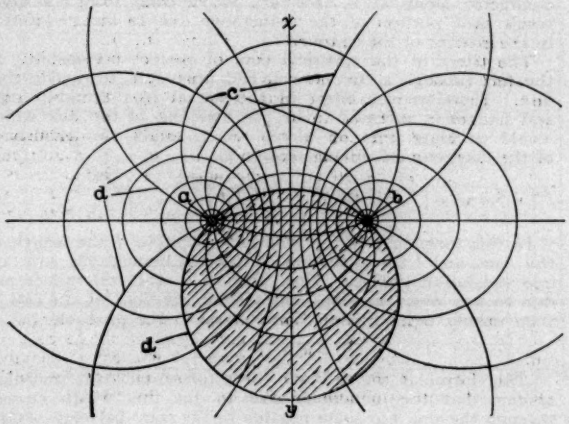


FIG. 2.

count the inductance due to flux within the slots. That must be calculated separately.

Mr. Allen, in his paper, shows that the inductance of a coil in commutation on an armature running in a frame is nearly the same as if the armature were running out of the frame. The fluctuations of current in the coils being commutated tend to set up variations of flux through the iron of the yoke. That iron is surrounded by coils of a large number of turns, which are in parallel with the armature and which act as the short-circuited secondary of a transformer. The effect of the short-circuited secondary is to oppose the variations of flux and nearly to nullify the effect of the iron in the yoke,

so that the total flux surrounding the coil is not much greater than if the armature were spinning in air. Whether the armature be spinning in air or in the fields an approximation can be made to the inductance of the coils by this method of taking an approximating circular coil, computing the inductance of the circular coil on a spherical core of perfect permeability, and adding to this the inductance due to flux within the slots. The details of the calculation will merely be indicated here.

In his "Treatise on Electricity and Magnetism," Maxwell gives the total inductance of a circular coil in air, due to flux circulating both around and within the material of the conductor. To find the inductance due to flux o tside the conductor alone, it is necessary to subtract from Maxwell's result that portion of the inductance due to flux circulating in the interior of the conductor.

The effect of the spherical core of perfect permeability on the flux through a circular coil laid upon it is to double that flux. Therefore the effect of the actual iron armature core and flanges is assumed to be the doubling of the flux which would circulate if in air alone. As a result, the permeance of the magnetic circuit in question is

$$P'' = 8.3\sqrt{p\,(J+l)}\,\log_{.10}\frac{1.13\sqrt{p\,(J+l)}}{a}$$

In this formula p is the chordal coil-pitch, J the length of the core, and l the extension of the coil beyond the core on one end, all in inches. That portion of the coil inductance due to flux over the slots and around the ends of the coil is then readily determinable, being equal to the product,

$$P'' \times n^2 \times 10^{-8}.$$

The formulas which have been presented this morning assume that the inductance due to the flux which crosses through the slot has some relation to the ratio between width and depth of slot. This flux has a definite relation to the width of the slot; it is inversely proportional. If the coil completely filled both slots in which its conductors lie, this flux would also be directly proportional to the depth of the slot, and that proportion of the coil inductance due to the flux across the slot would be proportional to the ratio, slot-depth ÷ slot-width.

Actually, however, the coil on one side lies in the bottom half of the slot, although not usually at the very bottom, and on the other side in the top half of the slot, although not usually coming clear to the top. Moreover, there is a space required for insulation and unoccupied by windings in the middle of the slot. Finally, a certain amount of flux crossing at the top of the slot arches up above the height of the teeth, adding to the effective slot depth.

Flux crossing through the winding which induces it has zero density at the bottom of this winding and increases to a maximum at the top of the winding. Below the winding no flux passes, and above the winding the flux density is constant at the maximum value. It results that the inductance due to flux through the coil follows a cubic law, while for that above the coil it does not. Careful computation requires that these factors be included. This is a matter of only the slightest additional labor, after the proper formula has once been written, and may affect the result by 10% or more.

In fact, after the determination of the formulas, the calculation of armature coil inductance by the method described is extremely simple, and may be done in a few minutes. The

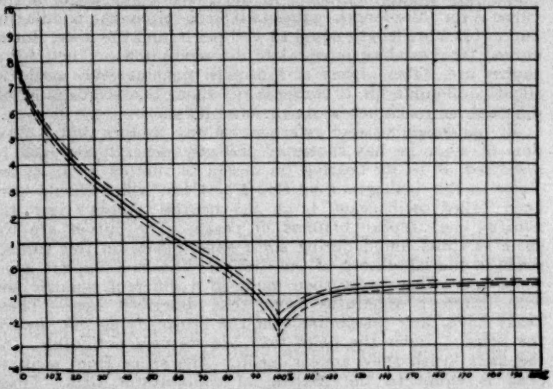


FIG 3.

results obtained are found to be quite accurate; for example, the computed permeance of the magnetic circuit of self-inductance about a certain armature coil was 233, while the experimentally found result was 229, an error of only 1.75 per cent.

Since part of the flux set up by an armature coil passes around the core and through other armature coils, the effects of mutual inductance on commutation are great. Coils in commutation, not only one or two bars removed from the coil in question, but even removed one coil-pitch, will have to be considered. The mutual effects of coils not in the same slot are due entirely to the flux which goes over the outside of the core and surrounds the end connections. This can be determined experimentally. Fig. 3 is a curve showing the

mutual effect of two coils when removed from each other by varying percentages of the coil-pitch. The effect is greatest when the coils lie near together, it becomes 0 at about 80% removal, is a negative maximum at full-pitch removal, and continues negative on around the core. For removal 0 per cent the coils coincide, and the ordinate of the curve represents that portion of the self-inductance due to flux around the core and around the end connections. The mutual inductance of two coils not in the same slot is therefore obtained by substituting the ordinate taken from this curve for the factor 8.3 in the formula for P'', the permeance of self-inductance due to flux around the core.

Great changes in the relation of core-length to coil-pitch make only slight differences in the curve. The upper dotted curve is for core-length equal to 0.5 coil pitch, the middle full curve for core-length equal to coil-pitch and the lower dotted curve for core-length equal to 1.5 coil-pitch. The curves shown are taken from a four-pole machine and would be slightly different for a two-pole machine, but scarcely at all different on machines of six or more poles.

Mr. Anderson's paper refers to railway motors, but a good deal of what he has shown is perfectly general, and will be discussed as to its bearing on design of motors of all types. Refer to the oscillogram entitled No. 3, but which should have been called oscillogram 4, at the neutral points, near the neutral line, appear systems of peaks. The curves are the same as those found during some experiments on this subject made in the laboratory of the Crocker-Wheeler Company some years ago. They were then made in a different manner and with different apparatus from that described here. These peaks have their maximum near the brush, dying out toward the poles. Under the poles they are scarcely noticeable. At the next brush they appear again. The space from peak to peak is equal to the spacing of commutator bars. These peaks are peaks in pressure between adjacent bars. As the commutator moves forward the pressure between two bars is continually varying as shown by the curve. Even when two bars are short-circuited by the brush these same waves are found. A curious thing found was that in the region lying a slight distance beyond the toe of the brush the curve is very unstable, so unstable that it is almost impossible to determine it. The form of the curve as a whole in this region appears to vary from bar to bar continually. This peculiarity has not yet been cleared up. As stated at the bottom of page 383 and top of 384, these peaks are caused by mutual inductance with other conductors being commutated, conductors which may be several slots removed from the coil in question, or even under the next pole.

There is a close relation between the heights and locations of the peaks and the operation of the machine. Under certain

conditions these peaks will be high near the heel of the brush, and under other conditions high near the toe. It is under the latter condition that severe sparking is found to occur. Slight visible sparking, or sparking which is invisible, being under the brush, may take place when high peaks occur back from the brush toe. The sparks caused by this may be carried forward to the toe and show slightly. Under conditions of heavy load or otherwise the peaks move forward until one of them reaches the toe, when the sparking becomes vicious. The difficulty in finding a satisfactory criterion of sparking arises from the difficulty in telling where the peaks will come and how high they will be. To determine this it will be necessary to take into account not only the self-inductance of the coil, but its mutual inductance with every coil which is in commutation.

R. B. TREAT:—There are so many independent factors affecting sparking that it does not seem advisable to collect them all within a single "Criterion of Sparking" formula. The collective result might be favorable—and the machine spark. Any one of the factors may be the disturbing one.

The equation given by Mr. Waters,

$$C = n^2 (l k + p c) N I f P Q$$

does not include several sparking factors equally important to those mentioned. We should, however, be grateful to him for presenting the "Inequality factor" to us in so tangible a form.

W. L. WATERS:—Mr. Anderson calls attention to the fact that in the oscillogram shown on page 381, the pressure is indicated at about four volts, whereas we should expect a self-induction pressure of only about half a volt. The explanation of this appears to the speaker to be quite simple. When running with brushes on the neutral point, we are, in reality, running in a magnetic field, which is by no means zero. The magnetic field due to magnets, is zero, but the magnetic field due to the cross magnetization of the armature is considerable. This is shown quite plainly in oscillogram No. 6. The fact that the short-circuited armature coil is running in this magnetic field causes a large short-circuit current to be induced in this coil, and it is the breaking of this short-circuit current rather than the commutating of the normal armature current which causes this high e.m.f., shown in the oscillogram. The correct way to obtain an oscillogram indicating the self-induction e.m.f. due to the commutation of the armature current would be to take the armature and run it without the field magnets, passing full-load current through it. This method was, I think, proposed by Gano S. Dunn about eight years ago.

Referring to Mr. Anderson's statement that you can run with impunity with 5, 6, or 7 coils per slot, the speaker wishes to point out that this is due to the peculiar conditions, which you have in a railway motor. The magnetic field at the neutral point varies very slightly as we move away from the exact neutral. The field due to the magnets is zero, while that due to the armature is at a minimum point. The result of this is that a small variation of the point of commutation from the exact neutral is not of much consequence. But these conditions do not by any means apply to the standard direct-current generator. The magnetic field at the point of commutation in a direct-current generator varies very rapidly, and hence the slight inequality of the position of commutation, caused by using four or five coils per slot, produces quite a considerable variation in the sparking conditions, so that the case of a railway motor must be considered as quite a special one in respect to the possibility of using several coils per slot.

THORBURN REID:—The speaker is very much interested in Mr. Waters' paper, especially with reference to the inequality factor, which appears to him to be an ingenious solution of that problem. Just what fact Mr. Waters' assumption was based on is not clear, the only one shown being the figure on page 373, and the speaker is unable to discover upon what physical fact that figure is based. Mr. Waters said it gave him a formula which enabled him to design dynamos within 10% of accuracy as far as sparking was concerned; that being the case, the speaker does not think the establishment of an actual basis for his assumption is a matter of any importance.

What the speaker especially wishes to draw attention to is the sparking constants given on page 378 and the cause of their variation with different numbers of poles. One part of that variation, he thinks, would be found to rest on one of the elements of the formula for the sparking constant; that is, the inductance e.m.f.

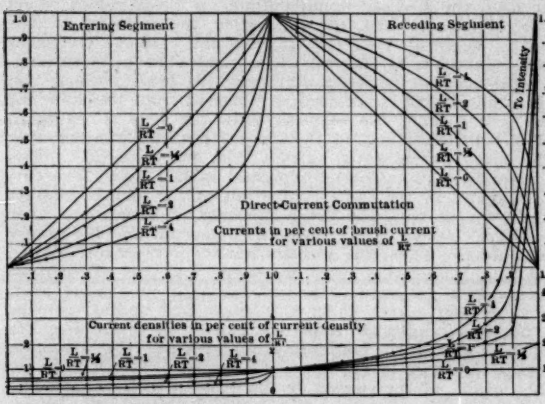
The speaker has been working for the last two or three years, as he got time, at this same problem of a sparking constant and has gotten his investigations nearly to the point where he is ready to bring them before the INSTITUTE. He is sorry he could not get them ready for this meeting, but has gotten far enough along to be able to give the members at least one piece of information on the subject that he hopes will be of value, and would like to give it now, in advance, in order that others who might have a chance to make experiments on the sparking constants of dynamos may be able to take up these constants by experimental work. The speaker has no facilities for doing this at the present time.

The speaker found that with one set of brushes the variation of the current from what might be called perfect resistance commutation depends, not on inductance e.m.f., but on the

ratio of the reactance to the contact resistance of the brush surface. The reactance pressure may vary very widely without affecting this ratio at all; on the other hand, the reactance pressure may remain constant and this ratio vary very widely. Mr. Waters' constant is based on reactance pressure alone and apparently as the number of poles increases there is a change in the ratio of the reactance to the contact resistance which has something to do with this change in his constant. If that factor were used in place of the reactance pressure, the speaker thinks he would find an entirely different relation in the variation of the constant. What it would be the speaker cannot say at the present time, because there is another factor affecting it of which he would speak later, which had come within the range of his investigation in the last few weeks. That ratio the speaker would put on the board which would enable him to present the matter to the members a little better. The factor is $L/R\,T$, L being the ordinary coefficient of self-inductance of the coil under commutation, R the contact resistance of the commutator for the brush surface, and T the time of the commutation reckoned from the time the brush first touches the segment until the time it leaves it. That factor determined, as the speaker has said, the variation of the actual commutated current from the theoretical. Perfect commutation might be expressed in this way. The current increases in the same proportion as the area of contact of the segment with the brush increases, in such a way that the current density on the segment is constant and the energy density developed on the segment surface is constant. When there is an inductance factor we would find that the current increases at a less rate than does the segment contact area, as the segment comes under the brush, and as the segment goes out from under the brush the current decreases at a less rapid rate, and as the coil inductance increases, that variation increases, as shown in the figure.

The density of the current in the brushes with straight-line commutation is constant. With the distortion due to inductance the current density gradually increases all the way from the beginning of the commutation to the end, and as the ratio L/RT increases and the curve varies still more from perfect commutation, the current density comes up higher and higher until finally at the end of the commutation period with high values of L/RT, the current density reaches infinity theoretically, so that the values of the factor L/RT enables us to determine, as the speaker will show when he is able to present his paper at the INSTITUTE, both the total increase of the energy developed at the brush contact-surface during the commutation period and the law by which this energy varies during the commutation period; and gives the means of forming a sparking criterion which the speaker hopes—he might say he ventures to hope—will be general in its application to all the different forms, at least of generators.

A further factor that affects this question is the frequency of the commutation periods. As a segment goes under the brush it receives energy in its different parts in different amounts; that is, the part that touches the brush first gets very little energy. The edge that leaves the brush last generally gets a maximum of energy with the result that the sparking or pitting usually occurs at the receding edge of the segment. The segment has energy poured into it through each brush as it passes underneath it; as it passes from one brush to the next, energy is conducted and radiated away. The speaker thinks the amount radiated has little bearing on the final temperature of the receding edge of the segment; that the main point is the amount that is conducted away


Entering Segment
Receding Segment
To Intensity
Direct-Current Commutation
Currents in per cent of brush current for various values of $\frac{L}{RT}$
Current densities in per cent of current density for various values of $\frac{L}{RT}$

towards the center and front edge of the segment, but during the time the segment is passing from one brush to the next, its temperature falls, and when it goes under the next brush it receives another block of energy which raises the temperature again, until finally, if the sparking constant is too high, the temperature is raised to the melting point and pitting occurs. The speaker has determined the increase of energy due to the increase in the sparking constant at each commutation period, thus leaving that to be multiplied by the number of commutation periods in a stated time in order to arrive at the total amount of energy poured into the receding edge of the segment, and that is the part of the investigation that he has not yet been able to take up. But he would like to ask those of the members who have had a chance to make

the calculation to use in their formulas the criterion of sparking L/RT in place of the inductance e.m.f., and see if it does not give them better results. The speaker thinks it will give better results because it is nearer the truth of the actual conditions of commutation.

The speaker would say one word in conclusion regarding the calculation of the self-inductance of the armature coil. He did a considerable amount of work on that some years ago and reached such very discordant results that he came to the conclusion that the simplest possible method of calculating the inductance, at least in practical work, was the best. Mr. Waters' method differs from his slightly, perhaps he should say it differs from it a good deal. Instead of using the total depth of the slot, as Mr. Waters did, the speaker used the depth of the slot above the winding. The width of the slot he used as did Mr. Waters. He had tried various other methods but did not find any of them to be especially accurate.

Mr. Waters has shown even by these rough values given for the sparking criterion some variation which has not been explained as yet, so that these very accurate determinations of the self-inductance seems to the speaker, at least at the present stage, to be refinements not warranted in practical work.

The speaker hopes that he will be able to present the formulas and curves on which his sparking criterion is based at an early date. As he had said before, he would be very glad indeed if any of the members who were able to calculate or make over their calculations on sparking constants would use the ratio L/RT in place of reactance pressure, and he will be glad to have any information on that subject, because he can assure the members that the investigation he has been making is about as complicated and as difficult as any he has ever tackled in his long experience.

E. H. ANDERSON:—One or two points the speaker would like to bring out. In the reactance formula, Mr. Waters says L is the length of the armature and K is the slot constant. Mr. Reid understood it to be the relative value between the width and the depth. The point the speaker wishes to bring out is this—that there is a permeance between tops of teeth in addition to that through the slot above the copper and through the slot where the copper is located. Including these three factors gives a permeance that works fairly well in determining the sparking value. However, in the discussion it was brought out that there was permeance from all tooth tops enclosed by coil which simply increases the estimated pressure possibly not over 10 per cent. Estimating by either of these methods will give a set of comparative numbers, and that is all the method gives anyway. A point was brought out by Mr. Reid which is good. One can calculate the tendency to spark according to Mr. Waters, but the actual com-

mutation depends upon how much energy is liberated on the commutator and how well the commutator handles it. Mr. Waters speaks from the direct-current generator standpoint, and the oscillograms given in the speaker's paper are from the railway-motor standpoint. The railway motor does not need to have its pressure across the commutator bars continuously. Consequently, we can use a radical distribution of conductors. We can use self-induction of commutation two or three times as high as in generators for the simple reason that the power is on at low pressure to start with; it rises with full intermittent current to full pressure and then the current drops, so that half of the distance through which the cars travel the commutator is polished. If there had been etching going on all the time, the commutator would not operate so well. Consequently, following out this idea, a railway motor on a particular duty may commutate well indeed; put it on another duty where the pressure and current are on longer, the motor may be heated somewhat more and the etching is too great for the polishing, with the result that the commutator does not run well. So it is possible to have the same motors on approximately the same service, but the service be different enough for one commutator to run bright and one to run black and give a lot of trouble in flashing. It comes down to the question that Mr. Reid brought out,—that the proper way to see whether a commutator is going to work satisfactorily in service is to find out how much energy is delivered to it and how much it can stand. However, the sparking value and the stability of the machine are a pretty safe indication as to commutation in service.

The large number of coils per slot and the high sparking quality all naturally go with a large motor in a small space, and it is only by reason of being in the railway service and having a polishing period that the commutator is really able to run so well. So that the question of design taken up in the speaker's paper relative to railway motors and the question of design taken up in Mr. Waters' paper relative to railway generators of course must be quite different. The speaker was very much interested, and agrees with Mr. Waters very decidedly in his inequality factor, because he has seen a one-coil-per-slot machine run very well although its calculated sparking was high. Three- and five-coils-per-slot machines require lower reactance pressure (calculated) in order to run as well, comparing somewhat in the order of 10, 7, and 6 for one-three- and five-coil-per-slot machines respectively.

W. S. FRANKLIN:—It seems to the speaker that the loss of pressure in direct-current machines on account of inductance of the armature sections is a phenomenon identically the same, from a physical point of view, as the "skin effect" in large wires. The analogy can be made clear as follows: on account of inductance in the armature section, the arma-

ture current is made to follow a larger resistance path in flowing through a section than it would if there was no inductance in the section, because then the current would go directly to the brush. The effect of inductance of armature sections is to increase the resistance of the armature between the brushes. On account of this increased resistance of the armature between the brushes there is an increased loss of e.m.f., exactly as in the case of a wire.

CLARENCE P. FELDMAN:—Mr. Waters considers only the self-induction of the windings and the effect of inequalities produced by placing more than one coil into each slot. Now it is well known that a four-pole series-wound armature will run without any sparking, even with the inequality produced by using, say, 93 coils and 47 slots.

On the other hand, he greatly underestimates the influence of the shape of the pole pieces; the main difference in European direct-current dynamos is to be found in the shape of the pole pieces, special forms of which have been patented by Kando, Arnold, and others. The reactance pressure, which is strongly advocated by so able a designer as Hobart, is a safe guide only for one special type of machine; it is merely a rule-of-thumb that has to be changed for every new design. A machine with high reactance pressure may work all right, and another one, with low reactance pressure, may show a tendency to spark.

Mr. Anderson's beautiful oscillograms, especially Fig. 1, page 381, show clearly the five points corresponding to the five coils per slot, a lower one and four of about equal height. His statement that a motor of identically the same design will commutate better at 250 than at 500 volts seems somewhat misleading or inexact. If he takes the same current at the same speed and half the field, the commutation will be worse; if he takes, as he probably intended, half the current at half the pressure, the commutation will be better, as he commutates one-half the current at one-half the pressure, or one-quarter the energy per bar.

The results obtained by Mr. Anderson with what he calls "standard fields" show that the short-circuited winding acts as a damper, impeding any rapid change of current or pressure. This explains the low rise of pressure in Fig. 8, as compared with Fig. 9, and the slow drop from it to *B*, Fig. 10, as compared with Fig. 11.

Mr. Reid has justly stated that not only the self- but also the mutual-induction between adjacent armature coils should be taken into account, and that other points, *i.e.*, the frequency of commutation, the contact resistance of the brushes, etc., are of marked influence upon commutation. He seems to be on the right path, but Professor E. Arnold, of Karlsruhe has, with the assistance of Professor Mie, now of Kiel, completely solved the differential equation for the case in question in

'98, and has lately, in his book on continuous-current machines, succeeded in showing the real shape of the commutating field for a novel design, taking the shape of the pole piece, self- and mutual-induction, number and width of bars, width and resistance of brushes, etc., in consideration. The single rule which he gave in his first paper was $\frac{TR}{L} \geq 1$, where

T = period of commutation.
R = contact resistance per cm.^{2}
L = inductance.

In his new book he completes his formula by giving all data necessary to figure self- and mutual-induction for any arrangement of coils in the slots.

W. S. FRANKLIN:—Whether mutual-inductance as well as self-inductance of the coils in a slot need to be considered in connection with the theory of commutation seems to be open to question. It is very doubtful if mutual-inductance has much to do with it. There is actually one current changing at one time, and that is the current in one coil, unless, of course, the brush spans three or four commutator bars, and then the mutual-inductance effects need to be taken into account.

THE PRESIDENT:—The paper yesterday showed that it did.

H. WARD LEONARD:—For the last 15 years the speaker has advocated the use of separately-excited field magnets for railway motors, in place of the ordinary series winding, and has pointed out theoretically the great difficulty that would arise by suddenly applying pressure to a series motor, indicating the results found by Mr. Anderson. The series motor formerly was generally used in elevator service, which is very similar to railway service, but has been practically given up for this use. The importance of having the field magnets fully excited when the pressure is applied to the armature is very clearly brought out in the paper in question. In examining the papers that have appeared in the last six months, on the single-phase railway motor, the speaker has been struck with the fact that the chief virtue claimed for the single-phase railway motor has been that it is a series motor, and therefore the only proper kind of motor for railway work.

The speaker has recently changed the field winding of an automobile motor from series to separately excited, and as a result, in addition to having more perfect control of the car, has found that the fields practically reach saturation at 120 watts, while the series field, on the same grade, required 1100 watts. The separately-excited field can carry 120 watts indefinitely, whereas with 1100 watts they would soon be destroyed. The principal reason, in the speaker's opinion, for the use of series motors is the matter of patents.

[COMMUNICATED AFTER ADJOURNMENT.]

THORBURN REID:—It was brought to the attention of the writer at the meeting by several members after he had spoken, that the sparking criterion, $L/T\,R$, has already been deduced by Arnold and Mie in Germany, a fact of which he was not aware at that time. In fact, the writer had not known of their investigations at all until some time after his own equations were deduced, which in their differential form are similar to Arnold's and Mie's, but in their integral form are entirely different.

The fact that the current density at the end of the commutation period would theoretically reach infinity for any value of $L/T\,R$ equal to or greater than unity, the writer had also deduced before he had heard of Arnold's and Mie's investigations, but while he agrees with them that sparkless commutation can probably not take place if $L/T\,R$ is equal to or greater than one, he is satisfied that sparking can take place for values of $L/R\,T$ very much less than unity and also that sparking may occur for values of $L/R\,T$ equal or greater than unity that will not, however, injure the commutator in any way. The writer's explanation of these facts is too long to give now and will be given in full in the paper he is preparing on the subject.

The writer wishes to add that on reading over his paper on "Sparking; Its Causes and Effects," read before the INSTITUTE in December, 1897, he finds that the method of analysis afterwards used by Arnold and Mie was suggested in it and that the sparking criterion finally reached by their analysis was given in the writer's paper with the difference that, as he had not at that time made any mathematical analysis, he did not know that the resistance of the coil under commutation could be neglected as compared with its reactance, and therefore gave the criterion as the ratio of the impedance of the coil under commutation to the segment contact resistance.

DISCUSSION ON "ON THE CALCULATION OF LINE BATTERIES."

F. J. WHITE:—Doctor Winship states that the best method of determining the average running current per car is by station wattmeter readings. That method will give the average current for the average car, but not the variation of the current throughout the line, and very often that variation will alter the location of the centre of gravity. Take, for example, an interurban line; it will be found that the traffic is heaviest near the city and that there is an increase of the average current of the car over this section, which throws the centre of gravity nearer that point. With regard to sub-stations versus the line battery, where the average schedule is light, say half-hour or hourly cars, we find the battery is more economical to install; that is, it is cheaper in the first cost and the running expense is considerably less. Of course, this only

applies where the consumption of power is small and the peaks are heavy in comparison to the average work.

LAMAR LYNDON:—The speaker notes the results that Doctor Winship has obtained correspond in general with those of M. Sarrat, of Brussels, who developed a graphic method which was published in the *Revue Electrique* of February, 15, 1904. The speaker also obtained similar results which were published in 1902, and which practically correspond with Doctor Winship's. In the formulas of M. Sarrat and the speaker, the internal resistance of the battery was considered, and this Doctor Winship has apparently neglected. The internal resistance of the battery is made up of a number of factors, the principal of which is polarization. There is a definite drop on discharge, and a definite increase of pressure on charge, and this factor must be reckoned with. Also the character of the generator from which the load is supplied must be considered; that is, in Doctor Winship's equations, V_1 and V_2 are considered fixed pressures, whereas V_2, at least, is variable; V_1 is variable unless the generator be compounded for constant pressure. The variation in the value of V_2 will shift the minimum point of line pressure; that is, the vertex of the parabola, indicated by equation top of page 396, will shift in its location between two stations with load changes.

The resistance of the battery is not merely of academic interest. Its practical importance may be indicated by citing some computations which the speaker made on an equipment for a line battery placed at some distance—five miles—from the power station and controlled by a constant-current booster in the station. Two sets of calculations were made. In the first the changes in V_2 with change of load were allowed for, but there was no account taken, however, of the change in the location of the point of maximum pressure drop; that is, the point of minimum line pressure. As one of the results, the booster required, worked out 24 kw. with a correspondingly large driving motor. A re-computation, in which the factor of change in position of minimum line pressure due to the drop in battery pressure on discharge was taken into account, showed that the proper size of booster for this particular piece of work was 12 kw. In other words, it cut the size of the machine in two, with its attendant losses.

In a constant-current booster, feeding a line battery, the total booster input is lost. This, therefore, is a practical question. Of course, with Doctor Winship's equations, if two or three values of V_2 are assumed, accurate results would follow; but as they now appear, the speaker should not say that they are general equations.

W. E. WINSHIP:—With reference to Mr. Lyndon's criticism that the virtual internal resistance of the cell should be taken into consideration in calculating a line battery. It has not been the experience of the speaker that it is possible to obtain expression of this sort which one could work with for this

purpose. The potential difference of a cell is a function of two variables: the current charge or discharge and the time of its duration. This potential difference is not a linear function of either of these variables, but is an extremely complex expression and the periods of discharge and charge are variable. The calculations as given in the paper conform with results obtained in experience to within one or two per cent.

With regard to variable running currents on different sections of a road. It is well to increase the average running current at points where grades occur, especially if they are long and serious, thereby allowing for the increased consumption at such points. The assumed currents can vary three or four per cent. and not affect the final results seriously. A variation of three or four per cent in the running current means a corresponding variation in the drop to the battery; this means only one or two cells difference in the installation, and one does not expect to calculate a line battery closer than this.

THE PRESIDENT:—The speaker is much interested in line batteries just now, having under consideration the equipment of eight sub-stations, and if it is decided to use batteries this will be the largest installation of batteries, judged from the standpoint of first cost, yet attempted. In general, however, when a regulating booster is not used. The speaker has always made it the practice to connect up a number of the terminal cells with a lead to each cell and connect these leads through single-pole switches to a bus-bar extending along the tier of cells, in such a manner that more or less cells could be cut in, depending on the daily load, in order that the battery may be kept properly charged when floating on the line. It is not unusual to install five to ten more cells than are needed in normal operation. The speaker usually installs a certain amount of capacity in battery plates and leaves room in the tanks for the installation of as much more as conditions, due to natural growth of the plant for a few years, may warrant. For this reason the best calculations seldom fit a case on the start, or if they do they are not correct for the plant soon after it is placed in operation.

DISCUSSION ON "DATA AND TESTS ON A 10 000-CYCLE-PER-SECOND ALTERNATOR."

F. D. NEWBURY:—The speaker had the interesting experience of testing this high-frequency generator. Mr. Lamme has given fully the results of these tests, but the speaker may add something of interest concerning how the tests were carried out and the incidents that occurred during them due to the use of this frequency.

MEASUREMENT OF PRESSURE.

As Mr. Lamme has said in the latter part of his paper, the Weston voltmeter was entirely unsuited for use at this frequency, on account of its high inductance. At the time the

generator was completed and ready for test, Mr. Walker had in the testing department an electrostatic wattmeter which he was developing at that time. By a very simple change in connections this wattmeter could be used as an electrostatic voltmeter, which gave an instrument obviously suited for measurement of pressure at this high frequency. The current taken by the instrument as a condenser was entirely negligible even at 10 000 cycles. The static instrument gave very satisfactory results both as a voltmeter and later on as a wattmeter in some tests for iron loss in samples of sheet steel. The Cardew voltmeter mentioned by Mr. Lamme was of low range—150 volts—and was used only as a check on the static instrument at low pressures.

Iron-Loss Tests.

Mr. Lamme mentions that difficulty was encountered in obtaining satisfactory results in the iron-loss tests. These tests were made in the ordinary way with separate direct-current driving motor, the losses being measured as part of the driving-motor input. The most important reason for this trouble was the small value of the iron loss compared with the friction losses. For example, at 150 volts and 3000 rev. per min., the friction loss is 4000 watts while the iron loss is less than 200 watts. In addition, any fluctuation in the supply pressure of the driving-motor circuit caused an exchange of energy between the revolving generator field and the electrical circuit that caused fluctuations in the electrical input to the motor.

Consistent results were obtained by taking a large number of independent readings and by plotting auxiliary curves in the following ways:

From the data for different frequencies preliminary curves were plotted with watts and field amperes as coördinates. In these curves the points from different tests checked closely for high inductions but for low inductions the points from different tests were widely scattered. In order to locate the lower part of the iron-loss curves, curves were drawn for different field amperes with watts and frequency as coördinates. These curves showed the loss very nearly proportional to the frequency. For this reason the lower part of these curves could be accurately drawn as they were very nearly straight lines. Final watt field-ampere curves were plotted from coördinates taken from the watt-frequency curves.

Short-Circuit Tests.

It was necessary to obtain a current reading with small pressure drop. A dynamometer with a small number of turns was secured for this purpose. A hot-wire ammeter was also tried. On account of the retentivity of the forged-steel field the residual pressure of the generator was large and at the high speeds was large enough to circulate full-load current through the armature on short-circuit. For this reason the magnetic circuit had to be demagnetized before each short-circuit reading.

EFFECTS OF THE HIGH-FREQUENCY CURRENT.

(a) The coils of the dynamometer used became very warm with small current. This was probably due to so-called "skin effect" of the eddy currents generated in the wire.

(b) The eddy currents in all parts of the circuit were very marked. The stray-fields were also marked. During tests it was necessary to separate instruments widely.

(c) With sheet steel of ordinary thicknesses temperature rise was so great on account of iron loss that nothing could be done.

(d) It was attempted to measure high pressures obtained from air-core transformer by spark-gap, but as soon as spark jumped an arc was formed which burnt up the needle points.

(e) Very marked resonance effects were obtained with an air-core coil and condenser of usual construction connected in series.

F. B. CROCKER:—It would be well to remind the INSTITUTE that Mr. Tesla had a machine similar to this one which he used in his high-frequency experiments in 1891. He had it operating at Columbia University, where he gave a lecture. This machine was designed to give about 10 000 cycles-per-second. (See TRANASCTIONS, Vol. VIII., page 267.)

DISCUSSION ON "NOTES ON FLY-WHEELS."

H. H. BARNES, JR.:—The suggestion is made in the paper that the angular variation of the prime mover is not necessarily responsible for the cumulative surging of alternators operated in parallel. The usual argument advanced to prove the opposite is the behavior of water-wheel driven units, with which cumulative surging is unknown. This argument, however, is not conclusive, as will be seen from a more careful consideration of the conditions.

Let us assume that two alternators direct connected to water wheels (turbines or impulse wheels) are thrown together a little out of step, thus producing oscillations, which, it is needless to add, will be natural ones. The two machines will then oscillate back and forth, one machine traveling too fast when the other is traveling too slow. But this variation in speed means a variation in the driving torque of the wheels. As the speed rises above normal the driving torque decreases and *vice versa*. We have, therefore, in this variation of the driving torque a parallel to viscous damping. This variation will assist whatever electrical damping there may be in the machines, and the alternators will settle down to steady multiple running.

Let us now consider for a moment the behavior of alternators direct connected to overshot water-wheels. If we assume that the same amount of water is delivered to the individual bucket, irrespective of variations in the speed of the wheel, the driving torque of the wheel will remain constant regardless of the speed, and the driving power will vary as the

speed, a condition tending toward instability. The conditions in this case, therefore, differ considerably from those existing when turbines are used. As a result of this difference, it seems highly probable that alternators direct connected to overshot water-wheels and equipped with heavy fly-wheels would not operate satisfactorily together and that cumulative surging would set in.

If we turn now to the action of a reciprocating steam-engine equipped with a delay dash-pot, or, better still, with an entirely-blocked governor, we see that in a broad sense the action of the engine strongly resembles that of the overshot water-wheel while it differs from that of the turbine. At all events, we are not justified in saying that because turbine-driven units operate successfully, alternators direct connected to reciprocating-engines would do so also if it were not for the lack of uniformity in their driving torque. The two cases are not sufficiently similar to be compared in this way.

The same may be said of belt-driven units. Furthermore, the fly-wheel effect provided is always much smaller for water wheels and belt drive than it is for direct connection to engines. This gives a higher natural frequency and consequently more vigorous electrical damping, which, in itself, is an additional source of stability in favor of belts and water-wheels.

The statement that with a 70% ratio of frequencies the angular variation of an engine running singly may be doubled upon throwing two machines together, needs a little explanation. We would certainly get this increase—according to the general laws of resonance—if the original displacement followed the sine law and had a period equal to that of a revolution of the engine. In reality, however, the displacement curve is irregular. When developed into a Fourier series, we find that the maximum amplitude usually belongs to the second term, which has a period equivalent to half a revolution of the engine. The amplitude of the first term, with a period equal to one revolution of the engine, is relatively small. As there is a doubling of the amplitude of the first term only, and an increase of but some 15% in the amplitude of the second term, it is really unfair to say that the maximum displacement originally calculated for an engine running singly is doubled upon throwing it in with others. This extreme case, it is safe to say, will never be realized in practice. We have, therefore, this additional margin of safety to protect us when we use the formula for fly-wheels suggested in the paper. Instead of getting cross currents equal to 25% of the full-rated current as a maximum—which we might get if the original displacement were doubled—we may expect to see the cross currents limited to 15 or 18% at the most. This additional margin is ample to take care of any unbalancing of load between the cylinders of the engine, or of any other similar emergency that may arise during routine operation.

W. S. FRANKLIN:—Two or three years ago the speaker worked out a mathematical development which bears upon this question; namely, the theory of hunting and its dependence upon field distortion and pressure regulation of alternators. A final equation was reached, the denominator of which covered two pages and the numerator seven pages of paper, hence it was never offered to the INSTITUTE.

In the case of an ordinary undamped mechanical oscillation the force of restitution for a given displacement is the same on an outward as on a backward excursion. In this case the oscillation has no tendency to grow larger and larger, and if there is any damping whatever it has a tendency to grow less and less. If, on the other hand, we had a mechanical system in which the force of restitution for a given displacement were greater on a return than on an outward excursion, there would be a tendency for the oscillations to grow more and more violent, unless the tendency is balanced by very great damping. Now, in the case of an alternator connected to a synchronous motor, we have conditions exactly analogous to this second case. That is to say, the forces which tend to bring the two alternators into their normal, steady, running relation with each other are greater while they are returning toward that state than while they are departing from it, and consequently their oscillations have a tendency to increase. The cause of this is as follows: in the first place any change in the e.m.f. acting on a system requires some time for the corresponding change of current to become established. In the second place, as two alternators oscillate with respect to each other, the resultant e.m.f. is continually varying in value, and the current conditions in the system do not keep pace with the changing e.m.f. conditions; so that the current values, while the system is departing from a certain state, do not correspond to the current values while the system is returning to that state. The result of this is that the oscillations of the synchronous motor are increased on account of the fact that torque values, which correspond to current, are greater while the system is returning to its steady running configuration than while it is departing from it. Therefore, any slight disturbance of the synchronous motor tends to cause a continual increase of violence of hunting oscillations unless balanced by damping.

Can Mr. Barnes say whether the increase of damping observed when the exciters were connected in parallel might not be ascribed to the fact that the field coils under these conditions act like short-circuited copper conductors around the field poles.

H. H. BARNES, JR.:—The speaker would say that as he understands Professor Franklin, we would get the same result if we excited the two alternators from one exciter.

W. S. FRANKLIN:—Yes.

H. H. BARNES, JR.:—If you excite from one exciter, you

also have the two field circuits in series. This was tried, but no change was noticeable in the surging; it proceeded exactly as it had done before when separate exciters were used. The following test was also made. Thinking that by cross-connecting the exciters we might possibly counteract the effect of any variation in speed and stifle the tendency to surge, each alternator was excited from the exciter of the other. But we found no change whatever in the behavior of the machines. The only way these machines could be made to hold together was by paralleling the exciters. Therefore the speaker believes that the only correct explanation is that we actually have a pronounced damping effect in the exchange of energy between the two exciters as the two alternators oscillate back and forth.

CLARENCE P. FELDMAN:*—Mr. Barnes is correct in saying that gas-engines driving alternators need less fly-wheel capacity and heavier damping. Mr. Rosenberg, formerly chief engineer of Koerting's Works at Hanover, has tested this point by paralleling three-phase alternators with light fly-wheels. It is not probable that it was by chance that Le Blanc, of Paris, made the experiments with his damper at St. Ouen with a single-cylinder steam-engine. Some two years ago, the speaker was asked to give his opinion upon the question of the operation in parallel of two stations in Italy, having alternators of different construction,—one with two slots per pole, the other with three, the smaller alternators had a less drop in pressure than the larges ones and very bad hunting resulted,—particularly when the smaller alternators were used as synchronous motors. The speaker advised heavier damping, and the use of self-induction in the line, but is not informed whether the remedy was successful.

As Mr. Barnes has said, Boucherot has given a formula for the fly-wheel,—perhaps the best there is. Professor Georges, of Dresden, has put the mathematical work into simpler form; he has done as Rosenberg did, that is, has made vector diagrams, and has shown, as Mr. Barnes has done, that the weight of the fly-wheel may be decreased when the prime mover has slight uniformity of angular velocity, as in the case of a gas-engine.

H. H. BARNES, JR.:—Referring to Professor Franklin's remarks, is the speaker correct in assuming that his explanation of the development of the inherent tendency to surge is independent of the angular variation?

W. S. FRANKLIN:—Oh, yes, indeed.

H. H. BARNES, JR.:—Therefore we do not have to introduce the angular variation of the engines to explain cumulative surging? Faulty paralleling, or a sudden variation in load, or a change in excitation will do as well?

---

*Polytechnic High School, Darmstadt.

W. S. FRANKLIN:—Not at all. It merely requires a disturbance of equilibrium. If you start the oscillations, and if the force of restitution is greater while the thing is coming back than while it is going outward, it will keep on increasing.

H. H. BARNES, JR.:—The speaker believes damping is a good thing in every case. He is thinking of it, however, less in connection with any effect it may have upon the angular variation of the engines than in connection with the inherent tendency to surge. Angular variation in the engine is, after all, not a serious drawback. But the inherent tendency to surge must be neutralized or counteracted in some way, or the machines will not hold together. And the best way to neutralize it is to provide sufficient electrical damping. As regards the various formulas that have been developed for the natural period of alternators, it is true that a number of others have worked along the same lines since Boucherot presented his original paper, foremost among them being Georges and Kapp.

W. S. FRANKLIN:—The speaker believes that the inherent tendency to hunting depends upon the inductance of the circuit, inasmuch as the inductance of the circuit is the chief factor which determines a delay of the building up of steady-current conditions in the circuit.

CLARENCE P. FELDMAN:—The speaker has never used a damper, but has frequently used steel pole-pieces, which, in themselves, act partly as dampers. In the first German alternating-current station, at Cologne, at first cross-connections were used with the exciters, but later each alternator had its own exciter; there was, however, no difference shown in the results. This station had at first 400-kw. machines, afterwards several 1000-kw. machines were added, and for a time the municipal authorities were afraid to operate them in parallel, on account of hunting. The larger alternators had a coefficient of angular variation of 1/350, with very heavy fly-wheels, and a regulation of 10% on non-inductive load; the smaller had a coefficient of 1/220, and a regulation of 18 per cent. The speaker advised that they could be operated in parallel without trouble, because the smaller machine would be pulled around by the larger, and this proved to be the case. The smaller machine could be used only on non-inductive loads; when used with motor-loads, they did not add appreciably to the output of the station. There was some trouble at the station at first; one of four identical sets gave signs of hunting; but the trouble was remedied by altering the dash-pot on the engine.

The question of hunting is very complicated; it may be started by partly electrical or partly mechanical disturbances. The speaker has had no trouble with hunting, having always used heavy fly-wheels, which, with the damping induced by the steel poles or by short-circuited coils on the pole-pieces, has prevented trouble of this character.

H. Y. HALL, JR.:—Professor Franklin made reference to the possible damping effect of the field coils of the alternators. The speaker has frequently noted, in connection with the alternators of the Manhattan Railway Company, that there is a slight continuous oscillation or vibration of the field-ammeter needles, which shows that there are induced currents in the fields. It has also been noted that whenever a dash-pot sticks or a valve-hook of an engine misses this effect is increased quite materially and that the increased oscillation is of the same frequency as the oscillation of the engine.

THE PRESIDENT:—In other words, the oscillations of the needle correspond to the stroke of the dash-pot?

H. Y. HALL, JR.:—Whenever it misses.

CLARENCE P. FELDMAN:—Boucherot has shown that the effect of the armature reaction of an alternator is transferred to the armature of the exciter by reason of its effect on the field of the alternator. In an old station, the speaker had an exciter with the field of sheet-iron, having a very high armature reaction; this exciter always sparked when exciting the field of the alternator, but did not spark when working on a water-load; the oscillating pressure produced in the field could be shown by means of a transformer; the difficulty was overcome by the use of a cast-iron field in place of the sheet iron. This may account for some of the advantages found by Mr. Barnes in connecting one exciter to two alternators, or in cross-connecting the exciters; possibly some damping effect was produced by putting them together.

H. H. BARNES, JR.:—The speaker believes the problem we have in this country, or which we have had, of getting alternators with heavy fly-wheels to operate properly together, has been somewhat of a special problem. They have not had the same difficulties abroad. They favor somewhat lighter wheels as a general thing in Europe, a fact that is partially explained by the number of three-crank engines installed as prime movers. In Europe, therefore, the question of resonance has been the more important one, whereas with us it has been cumulative surging. In this country the speaker knows of one plant only in which there is actual trouble due to resonance under operating conditions. He has not visited this plant, and is not able to speak from personal experience, but understands it is well nigh impossible to operate the machines in multiple. The natural frequency at normal pressure is 92 per minute; and there are 100 revolutions per minute; therefore we have a ratio of frequencies of 0.92, which is too close to unity to allow of satisfactory running.

DISCUSSION ON "THE SINGLE-PHASE INDUCTION MOTOR."

W. S. FRANKLIN:—The speaker regrets very much that Mr. Steinmetz is not present, as he had hoped to draw him out in the discussion of the paper by referring to what seems to be

a serious defect in Mr. Steinmetz's papers on the single-phase induction motor. The speaker does not think that Mr. Steinmetz has given us a really fundamental or basic theory of the single-phase induction motor. His papers of February, 1898, and January, 1900, are no doubt of very considerable value, but they are devoted almost wholly to the operation of various starting devices. In so far as starting devices change a single-phase induction motor into a polyphase induction motor, Mr. Steinmetz's theory and equations are correct; but it can hardly be said that he has given any theory at all of the characteristic activities of the single-phase induction motor, and what he has given is incorrect, in the opinion of the speaker.

Mr. Steinmetz's method is to approach the theory of the single-phase induction motor by making certain modifications of the equations of the polyphase induction motor. This method seems to complicate the theory unnecessarily, and the speaker does not see how Mr. Steinmetz can justify the modifications of polyphase theory which he makes in adapting it to the single-phase machine.

The theory of the single-phase induction motor given here approximates to the actual facts as closely as the so-called complete theory of the ordinary transformer and as closely as the so-called complete theory of the polyphase induction motor. These theories as ordinarily used by engineers for accurate calculations take account only of first-order effects of primary resistance, magnetic leakage, and core losses, the mutual disturbing influences of these things being always ignored, except only in a single case.

The speaker has refrained from giving the full algebraic development of the theory, thinking that an outline of the method of obtaining numerical results might be more intelligible; for the sake of clearness the vector diagram of the transformer is used as a basis, which in its application to the induction motor is usually called the Heyland diagram. The various aspects of the calculations as based on the Heyland diagram correspond exactly to the various aspects of the calculations as based upon pure algebraic developments.

The difference between this theory and that of Mr. Steinmetz may perhaps be best indicated by comparing the speaker's equation for torque with the corresponding equation of Mr. Steinmetz, and it should be kept in mind that this equation is a logical result in this theory, while the corresponding equation of Mr. Steinmetz is an assumption. Mr. Steinmetz's papers do not contain a theory of the single-phase motor.

This difference between Mr. Steinmetz and the speaker in regard to torque may be stated most clearly for the case in which magnetic leakage is assumed to be equal to zero. On this assumption Mr. Steinmetz finds torque to be proportional to $\left(n - \frac{n^2}{f}\right)$ where n is speed and f is primary frequency. The

correct expression for torque, however, for zero magnetic leakage, makes it proportional to $\left(n - \frac{n^3}{f^2}\right)$. Both expressions give zero torque at standstill and at synchronism, but the correct expression gives maximum torque at 1/3 synchronous speed while Mr. Steinmetz's expression gives maximum torque at 1/2 synchronous speed, magnetic leakage being zero.

The speaker does not agree at all with Mr. Steinmetz on the question of magnetizing current; the statements in the paper regarding magnetizing current do not result directly from the speaker's fundamental equations, and therefore any one who accepts the derivation of the fundamental equations may think as he pleases concerning the magnetizing current. The speaker is, however, pretty sure that the cross-magnetizing current in the motor represents the flow of energy from kinetic energy of rotor to magnetic energy of cross flux and back again, and therefore that this cross magnetizing has no influence upon the primary current, if the rotor is heavy, except in so far as it is not wattless, and to the extent that it is not wattless it creates a back torque which increases the load current in the primary exactly as a belt load would.

The idea of the carrying of the induced rotor currents around by the armature, because of their supposed time lag in phase, thus enabling them to produce the cross flux, is utterly wrong. Properly all phases should be referred to *primary current*, not to primary electromotive force, and if there is no great amount of core reluctance we know that the currents induced in the rotor windings by the pulsations of the main flux Φ are exactly in phase both in space and in time with the stator or primary current. It is only through the mediation of e.m.f. produced by rotation that a current can be produced in the rotor windings which is out of phase either in time or space with the primary current.

The speaker wishes to make a further statement in justice to Mr. Steinmetz; that Mr. Steinmetz does not pretend that his papers on induction motors supply a physical analysis of the activities of the single-phase motor proper. Those of you who have read these papers, of course, know that more than nine-tenths of the discussion and developments apply simply to the behavior of the motor with various starting devices, and of course, in that case, the motor being really, to a great extent, a polyphase motor, the theory of the polyphase motor does actually apply.

[COMMUNICATION AFTER ADJOURNMENT.]

A. S. MCALLISTER:—On page 439 of his paper Professor Franklin says: "When a two-phase induction motor has one of its stator windings detached from the source of supply, thus becoming a single-phase motor, the wattless component of the magnetizing current in the remaining stator winding is unchanged in value and the power component of this magnetizing

current is doubled." Experiments show that, under the conditions assumed, both the power and the wattless components of the current in the active primary winding are increased; the former being slightly more, and the latter slightly less than doubled. Thus, with a certain two-phase induction motor, operating without load at full speed, the following observations were made:

	PHASE A			PHASE B			CALCULATIONS—PHASE A			
OBS.	E	I	W	E	I	W	Cos ϕ	Sin ϕ	I cos ϕ	I sin ϕ
(1)	165	11.7	397	165	11.7	397	.203	.979	2.41	11.45
(2)	165	21.7	930	137	0	0	.259	.966	5.63	20.95

The active winding of the motor, in any case, forms the primary of a stationary transformer of which the exciting current must possess sufficient magnetomotive force to maintain the value of flux demanded by the impressed e.m.f. While the current in the rotor, which produces the flux in exact mechanical quadrature to the primary magnetism, has truly no component magnetomotive force to affect the primary magnetism, and the assumption of no space lag of such current is more or less in accord with facts, it is not proper to neglect the fact that the counter e.m.f. of rotation of the conductors of the secondary of the transformer through the flux produced by the exciting current in the rotor is in time-phase with such flux, and that the additional current which flows in the rotor conductors due to the difference between the transformer e.m.f. and this counter e.m.f. has a component of opposing magnetomotive force which materially affects the current required to maintain the primary field.

DISCUSSION ON "WAVE-FORM-VARIATIONS OF A LONG-DISTANCE LINE."

THE PRESIDENT:—The Chair would say that it seems to be difficult to get any accurate information from these companies operating on the Pacific coast, and as they have had the most general experience, whenever we can get any information from them we consider ourselves somewhat fortunate. It seems to be their policy, however, to keep their troubles to themselves, which is not a bad policy sometimes.

BLANK
PAGE

A paper presented at the 188th Meeting of the American Institute of Electrical Engineers, Chicago, June 21-22, 1904.

Copyright 1904 by A. I. E. E.

PROTECTION OF CABLES FROM ARCS DUE TO THE FAILURE OF ADJACENT CABLES.

BY W. G. CARLTON.

The matter of the protection of cables depends largely on the number of cables and amount of room available. This protection is needed in stations and sub-stations, also in manholes on underground work; on inside work there is generally available room for separating the cables, and for this reason it is easier to take care of them than in underground work. In general, similar protection can be used in either place, except that in underground work material must be used which will not be affected by water, as manholes are liable to be flooded. Protection of cables in manholes will be considered particularly.

In old conduit systems where a large number of ducts have been installed and no attempt made at separating them as they enter manholes, it is a difficult matter to protect cables. If, however, the work has been carefully laid out, plenty of room taken in manholes and the ducts spread so that there is a vertical space of from 8 to 12 inches between the two halves of the conduit line, it is much easier to ensure satisfactory protection. It should be borne in mind that a conduit line of a large number of ducts is not a desirable thing. Two independent lines will cost considerably more than a single line of the same capacity, but this extra cost is an insurance against future trouble.

On account of the large amount of energy carried by high-pressure cables their protection is of the utmost importance. High-pressure transmission cables operate usually at from 5000 to 15 000 volts and are nearly always three-conductor cables. It is to the protection of such cables that this paper refers particularly, although it will generally be found that protection

is needed more from burn-outs on low-pressure cables than from those on high-pressure ones. High-pressure cables are usually protected by automatic overload devices and, if these are satisfactory they will disconnect the cable before any large amount of damage is done. On the other hand, low-pressure cables may continue to burn without drawing enough current to cause them to be cut off. Cables generally break down in manholes due to poor work in jointing or to careless handling during installation. Various methods are in use for fireproofing and isolating them from one another.

A method employed in a number of places is to wrap the cables with asbestos paper or tape about 1/8 in. thick, using two layers and binding the asbestos on by means of steel or brass tape. The metal tape is wrapped either in an open spiral leaving an inch or more between turns, or with the edges touching leaving no open space. With the metal tape wrapped close there is less danger of the asbestos disintegrating on account of water in manholes or of other causes. The asbestos wrapping should be carried well into the duct. This protection has been found adequate by several large companies. Its life, however, is uncertain, particularly on underground work. One disadvantage is that in the case of loaded cables the heat is less easily radiated on account of the asbestos covering. Asbestos paper soaked in silicate of soda has been used for wrapping cables; this has the advantage of not requiring any metal tape for a binder, as the paper treated in this manner is cemented to the cable. It is doubtful if the silicate of soda treatment will be satisfactory for use in manholes that are likely to be flooded, although it should be in dry places.

A second method of isolating and protecting cables consists in providing separate chases or runways for them. Sometimes this is done by building special long and thin bricks into the wall of the manhole leaving them projecting so as to form a shelf. Soapstone slabs are also laid in the wall forming shelves or boxes for the cables. The cables may be further protected with asbestos if desired. It is difficult with this method of protection to make a satisfactory job where the cables enter the ducts unless there has been a very elaborate spreading of the ducts.

The third method of protection, which is very satisfactory when the cables run fairly straight through the manholes, consists of a covering of vitrified-clay tile. Ordinary single-duct

clay tile in 18 in. lengths is used, the tile being cut nearly through before baking so that it is easily broken in halves. The tile on the lower layer of cables is supported by means of light galvanized angle-irons run longitudinally through the manholes. The upper layers are supported on the lower ones. For the bends in the cables 45 degree curves with a 12 in. radius are used. These curves being laid in reverse similar to the letter "S" near the end of the manholes where the cable enters the duct. The tiles are laid in cement mortar forming a good mechanical piece of work and giving practically a conduit line through the manhole. One or two of the lower ducts should be left open at each end of the manhole for a space of about one-half inch so that water will drain from the conduit line. The principal objection to the use of tiling is, that in the case of trouble, making it necessary to remove a cable, the tiling must be broken out. Iron brackets are avoided by the use of tiling and there is no chance for current to flow from the lead sheath of one cable to that of another except such leakage as may occur due to moisture in the ducts. Personally, the writer is in favor of using the split-clay tile covering where possible, and asbestos paper and brass tape in other places.

High-pressure cables should be covered, not only to protect them from the failure of adjacent cables but also on ac·ount of the dangers which may arise from an unconfined arc. Oscillations may be set up which will produce pressures many times in excess of that at which the cable is working, and these high-pressures are liable to break down the insulation on the cables or on the switchboard apparatus, transformers, or generators, which may be connected to the cables. For this reason one large company in New York has installed on all cables within a mile of the power-house, in addition to the regular asbestos covering, a sheet-iron armor 1/16 in. thick. This armor being rolled and especially prepared to meet curves or bends in the cable, each section lapping the next one. This sheet-iron is clamped together so as to make a strong mechanical covering.

A manhole fire causes more trouble at the top of the hole than lower down, and for this reason the most important cables should be kept towards the bottom of the manhole. In the case of large manholes it will often be found desirable to build a partition wall longitudinally through the hole, making practically two manholes.

While burn-outs in cables are bound to occur—and for this

reason, fireproofing cables, particularly important ones, is necessary—at the same time, the number of burn-outs can be kept to a minimum by careful work. Only experienced and careful men should be allowed to train cables. The manhole should be built so that it is not necessary, or even possible, to make a short bend in the cable in taking it from the duct to the side of the hole. The jointing should be done by thoroughly reliable men and they should be given to understand that it is not speed which is wanted but first-class work. If it is not desirable to do the jointing as soon as the cables are pulled in, the ends should be sealed, first cutting them back far enough to be positive that there is no moisture present. Tests for moisture should be made if there is any reason to suspect its presence.

The experience of one company in Chicago has been that nearly all trouble that has occurred on three-conductor high-pressure cables has been due to defective joints, to moisture in the cables near the joints, or to sharp bends in the cable. Some burn-outs have occurred due to the lead sheathing of the cables being damaged by electrolysis. This can be prevented by grounding the lead of the cables at suitable intervals or by insulating them if possible. Frequent inspection should be made to determine whether the lead sheaths of the cables are carrying current, a recording voltmeter having a total range of from three to five volts will be found convenient for this work and a chart covering the entire day will be found much more valuable than a few single readings.

Discussion on "Protection of Cables from Arcs Due to Failure of Adjacent Cables."

Ralph D. Mershon: In addition to the protection of cables in manholes, there is also the question of the protection of cables in power-stations. It is not always easy to install cables in such a way that they will be protected from each other, especially if the power-house has not been laid out with reference to them. The question of protecting cables by means of asbestos and similar wrappings has for its chief objection that there is no chance to get rid of the heat in the cable. For that reason, and for the greater one of reliability, the speaker very much prefers either tile or brick protection to asbestos.

Mr. Carlton speaks of using a voltmeter for determining the current being carried by the cable sheath. Will Mr. Carlton please explain a little more fully the method of using the voltmeter, and also the method he prefers for permanent grounding of metal sheaths?

W. F. Wells: Mr. Carlton refers to two independent lines of subway as being an insurance against trouble on a high-pressure cable system. In New York this practice has been carried a little further, and four separate and independent trunk subways have been installed, leading from the generating station along four different routes. From these trunk subways run branches arranged so as to give each substation two or more feeders, following entirely different subway routes. In case of a manhole caving in, or general trouble on any subway line, not more than one quarter of the high-pressure cable system can be affected.

Regarding the injury to high-pressure cables by the burning out of low-pressure cables; this has occurred, but burn-outs have also originated in the high-pressure cables. Some of these troubles were due to defective joints and some to short bends in the cable where it leaves the duct. In order to obviate this latter cause, the cable is now run straight out of the duct 12 in. before bending it over to the side of the manhole, thus preventing the edge of the duct from cutting into the sheath of the cable.

For the past two or three years the high-pressure cables in manholes have been wrapped with asbestos bound on by galvanized-steel tape, as described by Mr. Carlton, and the results have been very satisfactory. No trouble has been experienced from the heating of the cables where covered with this asbestos wrapping. In the stations, clay ducts or iron pipes are used wherever possible to protect the lead-covered cables, and, when there is sufficient space, braided cables are carried on insulators through runways of brick 12-in. square.

H. C. Wirt: Will Mr. Carlton state whether he considers an underground line more reliable than overhead line as regards interruption of service?

Ralph D. Mershon: Mr. Carlton speaks of the extra ex-

pense of separating ducts. It seems that in some cases separation may not in the end be an extra expense. The capacity of the subway is not necessarily proportionate to the number of ducts in it. Allow a certain limiting value to the temperature of the cable, then the ducts near the center of the conduit will not be as effective as those outside, no matter how they are arranged; if they are separated, it might be cheaper in the end because of the greater capacity the two subways would have over the single. So far as the speaker knows there are no accurate data in regard to this matter. The speaker has done a little work himself in special cases, and some work was done at Niagara some time ago. Perhaps Mr. Carlton and Mr. Wells have some information on this subject.

W. G. CARLTON: In regard to the capacity of the cable being lessened in a larger conduit line; the speaker has no accurate information on that subject. Where cables are run at extremely heavy loads the gas generated inside of the cable will puncture the lead sheath, and this is one of the limiting features. The permissible watt consumption per linear foot of cable depends on the number of cables in one conduit line. With a single cable 20 watts per foot would probably be safe; with a larger number of cables, three or four might be the limit.

It is a good plan to treat the cables in the power-house—if they are lead-covered ones—practically the same as you would for underground construction. A conduit line can either be built, or when the cables are in place they can be covered with split clay tile. The ends of the cables need special care. Three-conductor cables must have some sort of terminal bell which allows spreading out the conductors for connection to the single-conductor cable, this bell to be filled with an insulating compound.

In regard to detecting possible stray currents on the lead sheaths of cables; a Bristol recording meter with a five-volt scale has been used; this is fairly satisfactory. A meter with the zero line in the middle of the chart and giving readings each side of this line would be much better. The voltmeter is connected between the lead sheath of the cable and a good ground. In our stations we connect with the ground plate; we have a ground bus-bar in our stations connected to several ground plates. In a manhole it would be connected to a water-pipe or sometimes to the cast-iron frame of the manhole or to a rod driven in the ground. The grounding of the cable sheaths is done ordinarily in the power-house, on the brass bell on the end of the cable.

Answering Mr. Wirt's question in regard to overhead and underground lines; in the case of one company operating possibly 75 miles of 9000-volt lines, 65 of which is underground, possibly 90% of the trouble on the lines is on the 10 miles of overhead line. This has been caused generally by boys throwing wires over the line, or by kite-strings.

H. B. ALVERSON: When the asbestos covering a cable is saturated with silicate of soda, the wrapping will harden and become nearly as good a conductor of heat as the lead jacket; this overcomes the objection that asbestos covering confines the heat within the cable.

W. G. CARLTON: How does that stand in a wet manhole?

H. B. ALVERSON: We have had no experience of that sort.

E. M. LAKE (by letter): In visiting some of the larger Eastern stations, about three years ago, it was observed that very little attention had been given at that time to the protection of outgoing cables. The bus-bars and immediate connections were protected by a most elaborate scheme of barriers built up of brick and concrete and of soapstone. The outgoing feeder lines, however, and in one or two places the main leads from the generators, were laid side by side upon cast-iron racks or upon thin sheet-steel shelves.

When this question came up in connection with the design

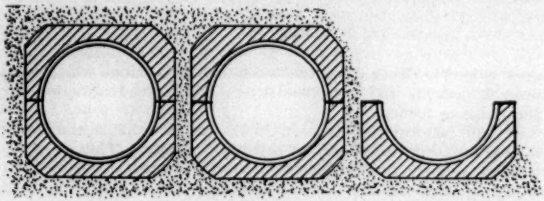


FIG. 1.

of certain Chicago sub-stations several methods were considered for protecting and isolating the whole cable equipment so as to reduce to a minimum the liability that a burn-out would spread to adjacent cables. The plan of using thin slabs of slate or vitrified clay was not found feasible because of the difficulty of applying in places where the structural work and cables were already in place. Then, too, this plan did not afford a simple and ready method of completely enclosing the cables where there were several in one run. Steel shelving and partitions when used alone were open to the same objections, besides being still further objectionable on account of the very small resisting power when subjected to the intense heat of an electrical burn-out. The proposition then narrowed down to some form of vitrified clay conduit because of the convenience of form, good mechanical strength, and high arc-resisting powers. Since the application must very often be made to cables in place, a split or divided form was necessary. There were found two forms of split conduit. One was divided in a straight line upon the diameter of the bore (Fig. 1). The other

was divided at an angle to the diameter, the two parts not being symmetrical (Fig. 2). These conduits were each applicable to certain conditions and locations, but a form was desired that would adapt itself readily to any and all places where protection of this kind was required. The style designed for this purpose was divided on lines parallel to the diameter of the bore but offset about an inch with reference to the diam-

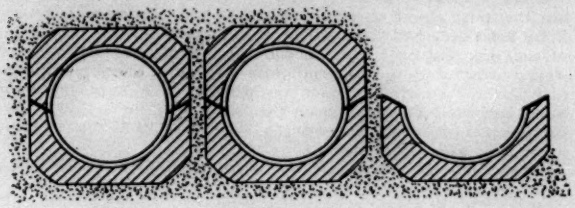


FIG. 2.

eter (Fig. 3). This gave two symmetrical sections which were interchangeable and possessed several distinct advantages over the existing forms.

It will be observed that in this form of conduit the joints in two adjacent ducts are not directly opposite. This of course insures a much more effective barrier between the cables enclosed by the conduit. For horizontal runs in walls the form

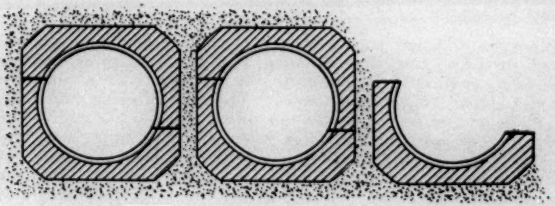


FIG. 3.

of the half-section is such that when laid it forms a convenient bed for the cable. Then when the cable is in place it does not form an obstruction to the laying of the remaining half of the conduit. Elbows on a safe radius for large cables and in an arc of 45 degrees were provided. Short straight lengths of 4½ in. and 9 in. were also ordered. With these forms and the standard 18-in. lengths it was comparatively easy to follow

the curves of any run of cables in a station or manhole, provided the cables had not been laid on less than a 12-in. radius.

A. M. HUNT (by letter): A covering for leaded cables where exposed in manholes can be made as follows: mix a stiff mortar using calcined magnesite (finely ground) and a saturated solution of magnesium chlorid; this combination hardens to stone in a few hours, and is heat-resistant and water-proof. Coat the lead of cable with oil, and wind it spirally with strips of canvas, putting the mortar on the inside of strip as the winding progresses. Any thickness of coating may be built up in this way. An outside finish of the mortar should be used. If the lead is not oiled, the mortar will adhere to it strongly, and be difficult to remove. The materials can be bought at prices which do not make the cost of such work heavy, and the covering is solid and effective.

As a protection against electrolytic action on the lead sheath of cables in an extensive network, the writer has tried operating a direct-current machine of low pressure with the negative terminal solidly connected to the lead sheathing and the positive strongly bonded to rails. The sphere of influence of this machine was much more extensive than might be imagined, and the application is worthy of consideration in cases where electrolytic action is severe. In the case noted the energy consumed was quite small.

J. W. F. BLIZARD (by letter): The writer suggests wrapping the cable in manholes with tape or thin asbestos, and then spreading a layer of about one-eighth inch of litharge on the cable. This will harden quickly and form a perfect protection from arcs, and may with ease be extended into the ducts for an inch or two. Ground mica and varnish would probably prove equally satisfactory, and cost considerably less. The asbestos or tape covering would prevent the compound used from adhering to the cable sheath, thus making the cable accessible in case of trouble, by simply breaking the protecting shell.

In addition to the dangers arising from the unconfined arc mentioned by Mr. Carlton, there is the often very serious one of gas explosions. No good ventilating system for underground conduits having yet been devised, this danger is an ever present one, and its importance should not be underrated.

BLANK
PAGE

A paper presented at the 188th Meeting of the American Institute of Electrical Engineers, Chicago, June 21-22, 1904.

Copyright 1904, by A. I. E. E.

SYNCHRONOUS MOTORS FOR REGULATION OF POWER-FACTOR AND LINE PRESSURE.

BY B. G. LAMME

General Discussion.

It is well known that the synchronous motor, running without load on an alternating-current circuit, for instance, can have its armature current varied by varying its field strength. A certain adjustment of field strength will give a minimum armature current. Either stronger or weaker fields will give increased current. These increased currents are to a great extent wattless. If the field is weaker than the normal (*i.e.* the field for minimum armature current), the increased armature current is leading with respect to the e.m.f. waves in the motor and lagging with respect to the line e.m.f. The current in the motor is therefore corrective in its nature. For stronger than the normal field, the current is to a great extent lagging and tends to lessen the flux in the motor and the current is leading with respect to the line e.m.f. A synchronous motor therefore has an inherent tendency to correct conditions set up by improper adjustment of its field strength. The correcting current in the motor is drawn from the supply system and this current also has a correcting effect on the supply system, tending to produce equalization between generated pressures in the motor and the supply pressure. This characteristic of the synchronous motor can readily be utilized for two purposes; namely, for varying the amount of leading or lagging current in a system for producing changes in the power-factor of the system (including transmission line, transformers, and generators), or a synchronous motor can be utilized for pressure regulation in a system.

As the synchronous motor can be made to impress a leading current upon the system, and as the amount of this leading current will depend upon the field adjustment of the synchronous motor, it is evident that this property can be used for neutralizing the effects of lagging current due to other apparatus on the system. The resultant leading or lagging current can be varied and the power-factor of the system can be controlled over a fairly wide range, depending upon the location of the synchronous motor or motors and upon the current capacity of the motor, etc.

As the wattless current in the motor is primarily a corrective current, it is evident that for most effective purposes for adjusting power-factor on the system the corrective action of this current on the motor itself should not be too great. When used for such purpose the synchronous motor should therefore be one which would give a comparatively large current if short-circuited as a generator. Also the motor should preferably be one in which the magnetic circuit is not highly saturated, for in the saturated machine the limits of adjustment in the field strength are rather narrow.

As has been noted above, if the field strength of the motor be varied, a leading or lagging current can be made to flow in its armature circuit, this current being one which tends to adjust the pressure of the armature and that of the supply system. It is evident that if the armature pressure is held constant and the supply pressure varied, a leading or lagging current would also flow. If for instance the line pressure were dropped below that of the motor, then a lagging current would flow in the motor tending to weaken its field, and a leading current would flow in the line, tending to raise the pressure on the line. If the line pressure should be higher than that generated by the synchronous motor, then the current in the motor would be leading, tending to raise its pressure; while it would be lagging with respect to the line, tending to lower its pressure. The resultant effect would be to equalize the pressures of the line and motor, and there would thus be a tendency to regulate the line pressure to a more nearly constant value. It is evident that the less the synchronous motor is affected by the corrective current and the more sensitive the line is to such corrective action, the greater the tendency will be toward constant pressure on the line. It is therefore evident that the synchronous motor which gives the largest current on short circuit as a generator would be the one which gives the greatest corrective action as regards pressure regulation of the system.

For such regulation, the synchronous motor which gives a comparatively large leading or lagging current with small change to the pressure of the system is the most suitable one. Or, the motor which gives the greatest change in the leading or lagging current is the one which gives best regulation. It is the change in the amount of wattless current which produces the regulation. This current could vary from zero to 100 leading, for example, or could change from 50 leading to 50 lagging, or could change from 100 lagging to zero lagging. Any of these conditions could produce the desired regulating tendency, but all would not be equally good as regards the synchronous motor capacity. If in addition to the regulating tendency it is desired to correct for lower power-factor due to other apparatus on the circuit, it would probably be advisable to run a comparatively large leading current on the line due to the synchronous motor, and the regulating tendency would be in the variations in the amount of leading current, and not from leading to lagging, or *vice versa*. A larger synchronous motor for the same regulating range would be required than if the motor were used for pressure regulation alone. It is evident that the current capacity of a motor regulating from 50 leading to 50 lagging need be much less than for current regulating from 100 leading to zero. It is evident therefore that if there is to be compensation for power-factor as well as regulation of pressure, that additional normal current capacity is required.

Regulating Characteristics as Fixed by Speed, Frequency, Etc.

In case such synchronous motors are required for regulation purely, it may be suggested that such machines be operated at very high speeds compared with ordinary practice. At first glance it would appear that such a synchronous motor could be operated at the highest speed that mechanical conditions would allow, but there are other conditions than mechanical ones which enter into this problem. For instance, it is now possible to build machines of relatively large capacity for two poles for 60-cycle circuits, and for very large capacities—say 1500 kilowatts—having four poles. Therefore mechanical conditions permit the high speeds, and the electrical conditions should be looked into carefully to see whether they are suitable for such service. As such synchronous motors should give relatively large currents on short circuit the effect of high speeds and a small number of poles on short-circuit current should be considered.

In order to give full-load current on short circuit, the field ampere-turns of such a machine should be practically equal to the armature ampere-turns, taking the distribution of windings etc., into account. By armature turns in this case is not meant the ampere wires on the armature, but the magnetizing effect due to these wires. Therefore to give, for instance, five or six times full-load current on short circuit, the field ampere-turns should be relatively high compared with the armature. This means that the field ampere-turns per pole should be very high, or the armature ampere-turns per pole very low. Experience shows that for very high speed machines, such as used for turbo-generators, there is considerable difficulty in finding room for a large number of field ampere-turns, and therefore in such machines it is necessary to reduce the armature ampere-turns very considerably for good inherent regulating characteristics. This in turn means rather massive construction, as the magnetic circuit in both the armature and field must have comparatively large section and the inductions must be rather high. This in turn means high iron losses in a relatively small amount of material compared with an ordinary low-speed machine, and abnormal designs are required for ventilation, etc., and for mechanical strength.

An increase in the number of poles usually allows increased number of field ampere-turns without a proportionate increase in the number of armature ampere-turns. This condition is true until a large number of poles is obtained, when the leakage between poles may become so high that the effective induction per pole is decreased so that there is no further gain by increasing the number of poles, unless the machine is made of abnormal dimensions as regards diameter, etc. Experience has indicated that in the case of very high-speed and very low-speed alternators, it is more difficult to obtain a large current on short circuit than with machines with an intermediate number of poles. For example, it is rather difficult to make a 600 kilovolt-ampere, 3600 rev. per min., two-pole machine which will give three times full-load current on short circuit. A 4-pole, 1800 rev. per min. machine can more easily be made to give three times full-load current on short circuit and with comparatively small additional weight of material. The material in the rotating part of the four-pole machine, while of greater weight, may be of considerably lower cost per pound. The stationary part of the four-pole machine may have a somewhat larger internal diameter, but the radial depth of sheet-steel will be less.

than in a two-pole machine. The total weight of material in the armature of a four-pole machine may be practically no greater than in a two-pole machine. Therefore a two-pole machine of this capacity should cost more than a four-pole machine, if designed to give the same current on short circuit. A six-pole machine would show possibly a slight gain over the one with four poles, but not nearly as much as the four-pole machine would over the one with two poles. The real gain of the six-pole over the four-pole construction would be in obtaining a machine which would give more than three times full-load current on short circuit. It would possibly be as easy to obtain four times full load current on short circuit with a six-pole machine as to obtain three times full load current on four-pole machine. An eight-pole machine would be in the same way somewhat better than the six-pole machine. Therefore if a 600 kilovolt-ampere machine giving six times full-load current on short circuit is desired, it would be advantageous to make the machine with possibly eight to twelve poles. The question of which would be the cheaper would depend upon a number of features in design.

If very large short-circuit currents are desired, then, as indicated above, the number of poles for a given capacity should be increased, or the normal rating of the high-speed machine should be decreased. If, for example, the 600 kilovolt-ampere, 3600 rev. per min. machine, mentioned above, should be rated at 200 kilovolt-amperes, then it could give nine times full-load current on short circuit; but such a method of rating is merely dodging the question.

In general, the following approximate limits for speeds and short circuit currents for 60-cycle apparatus can be given. These limits are necessarily arbitrary, and are intended to represent machines which could probably be made without using too abnormal dimensions;

600 kilovolt-amperes, 3600 rev. per min., two to three times full-load current on short circuit.

1000 kilovolt-amperes, 1800 rev. per min., three to four times full-load current on short circuit.

1500 kilovolt-amperes, 1200 rev. per min., four to five times full-load current on short circuit.

2500 kilovolt-amperes, 900 rev. per min., four to five times full-load current on short circuit.

For 25 cycles it is more difficult to give limiting conditions,

as the choice of speeds is very narrow. If, for example, a 1500 kilovolt-ampere, 2-pole, 1500 rev. per min. machine can be made to give three times full-load current on short circuit, then as machines of smaller rating cannot run at higher speed, the limiting condition of such machines must be the amount of current which they will give on short circuit. In the same way a 4-pole machine running at 750 rev. per min. may be made for 5000 kilovolt-amperes for three times full-load current as the limiting rating, and there is no choice of speeds for ratings between 1500 kilovolt-amperes and 5000 kilovolt-amperes.

It should be noted that the above speeds are very high compared with ordinary alternator practice and are up to high-speed turbo-generator practice, but machines with the above short-circuit ratings and speeds are probably more costly to build than machines of corresponding ratings at somewhat lower speeds. It will probably be found therefore that for the above maximum current on short circuit the cheapest synchronous motors for the given ratings will have somewhat lower speeds than those indicated above. It is certain that the lower-speed machines will be easier to design and will be slightly quieter in operation. Probably best all-round conditions will be found at about half the above speeds.

The above limiting conditions are given as only approximate and are based upon machines having ventiliation as is usually found on rotating-field generators for high speed. Artificial cooling, such as obtained with an air-blast or blowers, could modify the above figures somewhat; but in general it has been found that high-speed alternators can be worked up to the limit imposed by saturation before the limit imposed by temperature is attained. Therefore if higher saturation is not permissible, then there may be relatively small gain by using artificial cooling.

Synchronous Motors on Long Transmission Lines.

One of the principal applications of such regulating synchronous motors would be for controlling or regulating the pressure at the end of a long transmission line for maintaining constant pressure at the end of the line, independent of fluctuations of load or change of power-factor. In this case, increased output of the transmission line may more than compensate for the cost of the regulating synchronous motor. In such a case the synchronous motor not only acts as a regulator on the system but costs nothing in the end. In general, the more current that such a synchronous motor will give on short-

circuit, the better suited it will be for its purpose at the end of a long transmission line.

Where a number of such synchronous motors are installed in the same station, the field adjustment must be rather carefully made, to avoid cross-currents between machines; and the saturation characteristics of the various machines should be very similar. The better such machines are for regulating purposes, the poorer they are for equalizing each other by means of cross-currents.

As to the use of dampers with such synchronous motors, it is difficult to say just what is required. A synchronous motor on a line with considerable ohmic drop is liable to hunt to some extent, especially if the prime mover driving the generator has periodic variations in speed. If the synchronous motor gives very large current on short circuit, then its synchronizing power is high; this will tend to steady the operation of the motor and decrease the hunting. The writer believes that such motors in practice will be found to operate better and have better regulating power for constant pressure if provided with rather heavy copper dampers effectively placed on the field poles. With such heavy dampers reaction of the armature on the field is retarded, and therefore the armature may give a larger momentary current than would flow if there were no damping effect; in other words, the motor is more sluggish than one without dampers. Therefore the addition of heavy dampers on such a machine may produce the same regulating effect which would be obtained by a machine without dampers which gives a larger current on short circuit. Also a machine with heavy dampers will usually be the one with the least hunting tendency and therefore will have the least effect on the transmission line due to hunting currents.

A Synchronous Machine as Regulator and Motor.

In the above, the synchronous motor has been considered only as a regulator and not as a motor. It may be worth considering what would be the effect if the synchronous motor can do useful work at the same time that it regulates the system. In this case, with a given rated output, one component of the input will be wattless, and the other part will be energy. The ratio of these two components could be varied as desired. For example, considering the input as 100, the wattless component could be 60 when the energy component is 80; or the synchronous motor could carry a load of 80% of its rated capacity, this load including its own losses, and could

have a regulating component of 60% of its rated capacity. If the motor is used as a regulating machine only, then its wattless component can be practically 100. It appears therefore that the machine could be used more economically as both motor and regulator than as a regulator alone, but in such case it would probably be advisable to run the motor at somewhat lower speed than if operated entirely as a regulator. This reduction in speed may practically offset the gain in apparent capacity by using the machine for a double purpose. Also there is comparatively limited use for large synchronous motors for power purposes, as better results are usually obtained by subdividing the units and locating each unit nearest to its load. If a load could be provided which would permit very high-speed driving, then it would probably be of advantage to utilize the synchronous motor for driving.

Synchronous Converters as Regulators.

As the synchronous converter is one form of synchronous motor, the question of utilizing such machines for regulators should be mentioned. Upon looking into the question of distribution of losses in the converter, it will be noted that the losses in the armature winding are not uniform. Investigations show that at 100% power-factor the lowest heating in copper is obtained, and that any departure from this power-factor shows considerably increased loss in the copper, such loss being very high in certain portions of the winding. Next to the taps which lead to the collector there are strips of winding which at times are worked at a very high loss. Experience shows that it is not advantageous to operate converters at a low power-factor, and that if so operated continuously, or for any considerable periods, the winding should be made much heavier than for higher power-factors. Also in the usual design of converters the field is not made as strong compared with the armature as in alternator practice, and therefore the regulating tendency of the converter compared with a generator or ordinary synchronous motor, is low. Synchronous converters can and do act as regulators of pressure for sudden changes of the supply pressure, but such correcting or regulating action should not be continual; that is, the pressure supplied to a converter from a line should nominally be that required by the converter for best operation as a synchronous converter. Unless designed for the purpose, a synchronous converter should not be used to correct low power-factors due to other apparatus on the circuit.

RELATIVE COSTS OF SYNCHRONOUS MOTORS AS REGULATORS.

In the above considerations only general reference has been made to the cost of synchronous motors for regulating pressure and power-factors. It is difficult to give even approximate figures for relative costs of such apparatus. As intimated before, there is some mean speed or number of poles which will be the most suitable for giving a certain maximum current on short circuit. For speeds slightly above or below such mean speed, the cost of the synchronous motor should vary almost in proportion to the speed, provided the maximum short-circuit current can be diminished somewhat at the same time. If the speed is further increased or further decreased, the cost will tend to approach a constant figure. As the extreme conditions are approached, the cost will begin to rise. The above assumptions are on the basis of continuous operation at a given current capacity, this being the same in all cases. The above assumption is on the basis of decrease in the maximum short-circuit current, as the machine departs from the mean, or best speed. If the same maximum current is required, then the lowest cost should be at the mean or best speed, while at either side the cost should rise.

It is evident that it would be difficult to give any figures on relative costs of such apparatus. The machine for the best or mean condition, should cost practically the same as an alternating-current generator of the same speed, output, and short-circuit characteristics. As this speed would probably be somewhat higher than usual generator speeds, the cost of such machine would therefore be somewhat lower. This cost would be to a considerable extent, a function of the current on short circuit for a given rated capacity of machine. As mentioned before, in giving a table of limiting speeds and short circuits, it is probable that one-half this limiting speed would be near the best condition. Such machines would probably cost from 60% to 80% as much as similar machines for usual commercial high-speed conditions, neglecting turbo-generator practice. The frequency has considerable effect on this, as, for example, there is small choice of speed as regards high-speed 25-cycle machines. Taking very general figures only, it is probable that in the case of a given capacity of machine for say three or four times full-load current on short circuit the cost cannot be expected to be lower than one-half that of machines of similar rating at ordinary commercial speeds, turbo-generator practice being excluded. The costs in general should approximate more nearly

those of turbo-generators; but again, an exact comparison cannot be made because in usual practice the turbo-generators do not give three to four times full-load current on short circuit.

Some Other Elements in the General Problem.

There are a number of other conditions in this general problem, such as the advantage or disadvantage of placing synchronous motors in the main power-house, or distributing them in a number of sub-stations. Also there is the question of the effect of the cost on the generating plant when used with such regulating synchronous motors. If higher power-factors are maintained on the transmission system and generator, a cheaper form of generator can probably be used. The high power-factor permits a larger output from the transmission system and thus represents a gain. If the synchronous motor can be operated at its best speed and also do work, then there is a further gain. If the synchronous motor should be located at the center of power distribution, and the power is distributed through induction motors, then there is a possibility of reducing the cost of such motors by designing them for a lower power-factor, this being compensated for by the synchronous motor delivering leading currents. As the cost per horse power of small motors will be much greater than the cost per horse power of a large regulating motor, there is a possibility of gain from this source. If the induction motors are distributed over wide territory, this gain would be lessened and might disappear.

It should be mentioned that the power-factor of a system as influenced by difference in wave form has not been considered in the preceding discussion. It is obviously impracticable to neutralize by a synchronous motor the effect of currents in a system due to difference in wave form. Such currents will in general be of higher frequency than the fundamental wave of the system, and the synchronous motor obviously could not correct for them, unless it impressed upon the system opposite waves of the same frequency. This would mean a synchronous motor with a different wave form from that of the system.

The power-factor of a system will also be affected by any hunting of the apparatus on the system. It is evident that the synchronous motor could not correct or neutralize such effects, except through exerting a damping effect on the system and other apparatus on the system. A synchronous motor with heavy dampers can reduce the hunting in a system, but such hunting can also be damped by induction motors with low-resistance secondaries, especially if of the cage type. This

correcting effect should therefore be credited to the damper rather than to synchronous-motor action. There are a number of other questions which arise in connection with this regulating feature of the synchronous motor, but the subject is too broad to permit even mention of them.

Summary.

The substance of the preceding statements can be summarized as follows:

1. A synchronous motor can be used to establish leading or lagging currents in its supply system by suitable field adjustment, and can thus affect or control power-factor or phase relations of the current in the alternating-current system.

2. A synchronous motor will set up leading or lagging currents in its supply system if its field strength is held constant, and the pressure of the supply system is varied above or below that generated by the synchronous motor. Such leading or lagging currents in the supply system will tend to vary the pressure of the system. A synchronous motor can thus act as a regulator of the pressure of its supply system.

3. This regulating action is greatest with synchronous motors which have the closest true inherent regulation (as indicated by high field magnetomotive force compared with the armature magnetomotive force) in distinction from machines which have close apparent regulation obtained by saturation of the magnetic circuit.

4. If the synchronous motor is used both for regulating the power-factor for neutralizing the effect of other apparatus on the circuit, and for regulating or steadying the pressure of the supply system, its normal capacity for regulating will be diminished.

5. The most suitable speeds for best electrical conditions will in general be considerably below highest possible speeds as limited by mechanical conditions.

6. Heavy dampers will increase the effectiveness of the regulating tendency.

7. If the synchronous motor can be used for power purposes as well as for regulation, its apparent capacity is increased. This is due to the fact that the regulation is obtained by means of a wattless component and the power from the energy component, and the arithmetical sum of these two is greater than their resultant which fixes the current capacity of the machine.

8. Synchronous converters in general are not suited for reg-

ulating the pressure or controlling the power-factor of an alternating-current system.

9. The costs of synchronous motors for regulating purposes will in general be lower than for alternating-current motors or generators of customary speeds, and will approach more nearly to turbo-generator practice.

BLANK
PAGE

Discussion on "Synchronous Motors for the Regulation of Power-Factor and Line Voltage."

F. O. Blackwell: In a large plant it is an unnecessary extravagance to figure the copper for a low power-factor when the power-factor can be made 100% by adding leading current to the lagging current caused by induction motors. Even a small lagging power-factor increases the amount of copper very greatly for any assumed regulation.

Rotary condensers are also of great advantage in permitting the pressure of a power transmission system to be regulated at the centre of distribution. It would be perfectly possible to run a power transmission system with rotary condensers in the sub-station without any communication between the sub-station and the distant power-house. The first case of the use of a rotary condenser that the speaker knows of was in a Southern cotton-mill which was equipped with about 4000 h.p. of induction motors and 3000 h.p. of generators. The pressure and the current at the generators was excessive on account of the low power-factor of the load and something had to be done to relieve the apparatus. By installing a rotary condenser of 500 apparent kilowatts capacity in the mill the pressure at the generator, if the speaker remembers correctly, was cut down about 15% and the current was reduced about 20%. The rotary condenser also greatly improved the regulation of the system and avoided the installation of a new generator in the power-house, which would have otherwise been necessary and would have cost several times as much as the rotary condenser.

A 6000 h.p. plant in India, which transmitted power 90 miles, reached the limit of its capacity. The owners decided to increase its capacity by installing a 1000-kw. rotary condenser, and they have been enabled to transmit 50% more power over their existing line, with the same regulation as they had originally with the smaller amount of power. If it had not been for the rotary condenser they would have had to construct an entirely new transmission pole-line.

It is possible not only to maintain 100% power-factor in a transmission system, but also a leading current which will boost the pressure over the reactance of the line and step-up and step-down transformers, so that you can have as high a pressure at the sub-station as at the power-house, or even a higher pressure.

Of course, if a synchronous motor can be used to do useful work it is more economical than a rotary condenser. The most efficient power-factor would be 70% leading, at which point the energy and wattless components of the current are equal. You would then get 70% of the rated capacity of the motor for work and 70% for rotary condenser action.

As Mr. Lamme has pointed out, the high-speed, steam-turbine alternator is not the cheapest machine that can be de-

signed. A speed of about one half that used in turbo-alternators avoids all extreme strains which require special materials and methods of construction and is therefore more economical in design.

W. L. WATERS: This paper is a suitable sequel to the paper which Mr. Lincoln read last year on the "Choice of Frequency for Transmission Lines." Mr. Lincoln showed that if the power-factor on a transmission line was low, the amount of power which could be transmitted over that line, with reasonable regulation, was surprisingly small, and it followed from this that the power-factor should be kept as near as possible to unity.

Mr. Lamme is not quite clear when he describes the effect on the regulation of an over-excited synchronous motor. The beneficial effect of a synchronous motor is entirely due to the leading current, which it takes from the line. The amount of leading current which a motor can take from the line is decided by two things: 1. the margin in ampere-turns, which we have on the magnets. 2. the current in amperes, which the armature can carry.

Both of these are limited by the heating of the magnets and armature, so that, if we are manufacturing a synchronous motor for regulating the pressure on the transmission line, the correct rating of that machine should be the amperes of leading current which it can take when running at a given pressure without the temperature rise of the magnets or armature exceeding 40° cent. The normal rating of the machine and the short-circuit current tell you very little as regards the value of the machine for producing leading currents. We might have a large motor capable of giving a large short-circuit current, which, at the same time, was valueless for pressure regulation on account of the fact that we could not over-excite the magnets because their temperature rise was already high.

As the rating of the motor, as above suggested, is entirely limited by temperature, the force of Mr. Lamme's remark that turbo-alternators are unsuitable for this work becomes very plain. Those who have had experience with these very high-speed machines know that the great difficulty in designing them is to obtain low temperature rises, especially on the field magnets. The other objection to high-speed machines, that they are less reliable in operation, is not of much importance in the case where these motors are used exclusively for regulation of the power-factor. So considering only the question of temperature rise, probably the most economical machine would be one in which the output was about 250 kw. per pole in a 25-cycle machine and about 125 kw. per pole in the 60 cycle.

Mr. Lamme calls attention to the inherent regulating power of a synchronous motor. This effect certainly exists, but under ordinary conditions it is unimportant, and the main

use for the synchronous motor as a pressure regulator would be as a hand-operated regulator. In this respect, Mr. Lamme's statement that "the motor should preferably be one in which the magnetic circuit is not highly saturated," is incorrect, because a motor which had saturated magnets would have a much greater inherent regulating capacity than one in which the magnets were unsaturated; if the motor were infinitely large and perfectly saturated its inherent regulating capacity would be perfect. This statement, as regards unsaturated field magnets, is also incorrect if we consider the motor as being hand regulated, because the effect is one of ampere-turns and not of magnetic flux; that is, assuming the magnetic leakage is not excessive.

The effect of copper dampers on the pole pieces is only a time effect. They slightly delay the effect of a sudden rush of leading or lagging current, but in any case this effect only applies to the inherent regulating automatic action of the machine, so that for all practical purposes the effect of dampers on the pole pieces can be neglected, except as regards their effect on the hunting of the system. In regard to this hunting, Mr. Lamme's statement that squirrel-cage induction motors are more powerful as dampers than motors with coil-wound secondaries and collector rings, is not correct. The damping effect of an induction motor is greater the lower the resistance of the secondary. If we consider modern commercial induction motors, that is, motors capable of starting under full load without taking excessive current, then the resistance of a squirrel-cage secondary is about five or six times that of a coil-wound secondary with short-circuiting device, and in consequence the damping effect of the squirrel-cage armature would be proportionately less.

The question of the use of a synchronous motor running light as a pressure regulator is entirely a commercial question, and the advisability of its use in any particular case must be decided by the question whether the cost of this motor is more than compensated for by the increased output obtained from the line.

H. B. GEAR: This question has been discussed thus far with reference to the compensation of systems where the low power-factor was due to lagging current.

In a system operating at 40 000 volts with 200 miles of line the conditions may be reversed, the low power-factor being due to the component of leading current caused by the charging of the line. In such a system the kilovolt-amperes required to charge the lines amount to about 1800. It therefore requires a load of 3000 kilovolt-amperes at 80% lagging to bring the power-factor of this system up to 100%.

The use of a synchronous motor in compensating for a low power-factor on such a system would therefore be limited to the compensation of leading current up to the point where

the load of induction motors reached 3000 kilovolt-amperes. Under certain conditions it might therefore be possible to install a synchronous motor of relatively small capacity, using it during the light-load period to compensate for leading current and during the heavy-load period to compensate for lagging current.

W. B. JACKSON: All of us must appreciate that this paper upon synchronous motors is an excellent and timely one. Although the question as to the proper use of synchronous apparatus has been recognized as quite important for a number of years, yet it is assuming much greater importance as the great transmission systems are becoming more common.

One phase of the use of synchronous motors has not been touched upon in the paper. In the construction of our power transmission plants receiving their power from water, it is not unusual for the hydroelectric portion of the plant to be developed to a point far beyond the minimum capacity of the water. Consequently an auxiliary steam plant is installed to assist during low-water periods. Under such conditions there is often an excellent possibility for the plant to be so designed that the generators in the steam department may be used for balancing motors during the time of heavy load upon the hydraulic plant. It is readily appreciated that at times of low water or of serious back-water conditions the transmission department of the system will be lightly loaded and that, therefore, ample electrical capacity will be at hand to take care of a lower power-factor without difficulty so far as the transmission department is concerned, and at the same time we have the steam auxiliary in operation which will act as the balancing factor upon the system.

Why should not any such plant be so arranged that the engines and generators can be readily disconnected during the times when balancing by synchronous motors is desirable? In other words, when we have the transmission side of the system loaded to its utmost capacity? There is no reason why the possibilities of our auxiliary generator as a balancing motor should be lost sight of simply because it is normally connected to an engine. It is not at all difficult to arrange to disconnect these alternators from the engines and use them for balancing machines, thus making a double use of the apparatus that is installed for the auxiliary plant.

The reversible use of alternating-current generators in transmission plants, either as generators or motors, as the occasion may require, is not uncommon, but the reversible use of the machines as generator or balancing device is quite a different question.

Reference is made in the paper to the possibility of so installing synchronous motors upon the circuit that they may be caused to hold the pressure at the end of the line as high or even higher than that of the generators. There are several

plants where such use has been made of synchronous motors for years past; in fact, there are two plants that the speaker knows of where it has been customary to operate generators at approximately the same pressure as at the distributing end of the line, these being plants where a large part of the capacity of the plant was supplied to synchronous motors, and where it was possible to get into communication with the several synchronous motor installations without difficulty from the power-house. It would probably not be difficult to find plants where it would be practically impossible to operate at all were the synchronous motors now installed replaced by induction motors.

F. A. C. PERRINE: The suggestion Mr. Jackson has just made is a very important one, and we all would perhaps be interested to learn that it has been quite extensively used in some Western plants, and in connection with reserve steam machinery for compensating for large leading current on the line, and also automatic compounding of the synchronous motors. For example, in the steam station of the Oakland Transit Company, Oakland, California, supplied by the Old Bay Counties system, transmission of 140 miles, they were compelled to have a steam reserve, on account of fluctuations in pressure. F. H. Baum, one of our members, was called on to determine what could be done, as on account of the very heavy leading current when the load was light the pressure went up, and when the load was heavy the pressure went down. The fluctuations of the pressure were of a serious nature.

Mr. Baum compounded the exciter for the synchronous motors by the direct current, using an extra winding on the exciter, and he arranged this compounding so as to maintain a constant pressure on the system and almost a constant power-factor automatically without any hand regulation of the machine or the synchronous motors. He found, furthermore, by examination with an oscillograph, that Mr. Lamme has apparently not made himself understood on page 552, as he says it is not possible by means of the synchronous motor to correct errors in wave form. In the latter part he says: "such currents will in general be of higher frequency than the fundamental wave of the system, and the synchronous motor obviously could not correct for them, unless it impressed upon the system opposite waves of the same frequency. This would mean a synchronous motor with a different wave form from that of the system." That is exactly what the synchronous motor does at the end of a long line; at the end of a long line the initial wave form is very seriously distorted, and the synchronous motor having a wave form similar to the generator corrects for the variation induced at end of the line.

Again, in some of the mining plants supplied from long-distance transmission lines where the charge has been made on the basis of the maximum current, they have found it advan-

tageous to install synchronous condensers for maintaining high power-factor, the plant being operated by induction motors, the synchronous condenser being used as a reserve steam generator when, by reason of any accident, the power from the transmission line was interrupted.

As regards small plants where it is necessary to maintain a constant power-factor—and the power-factor is already reasonably high, due to the use of lighting load entirely—the synchronous motor as a regulator can be conveniently used, especially where a combined railroad and lighting load are operated from the same generator, and this again, by compounding the synchronous motor through its exciter from the direct-current end of the system. And again, this is used in connection with the steam-driven alternator auxiliary; that is, where a large alternating-current generator is employed during periods of light load, that load can be carried from a separate steam-engine of lower capacity driving an alternating-current generator. When the load rises beyond the capacity of the small engine the latter can be cut off and the load carried from the large alternator through the synchronous motor, the latter being compounded through the direct-current side and thus the power-factor maintained. This does away with the greatest objection to the installation of synchronous motors; the use of the synchronous motor gives the operator control of the whole system.

The matter of cost as presented by Mr. Lamme is surprising; not because he states there is a certain speed at which we find a minimum cost, but due to his statement that the cost of the synchronous converter will be from 60 to 80 per cent. of the cost of an ordinary-speed generator. If we take a generator having about 100 revolutions per minute, cost will be about ten dollars a kilowatt, while high-speed machines recently sold for four dollars a kilowatt. And this shows, furthermore, that the use of the synchronous motor as a condenser is about as cheap a regulating machine as can very well be obtained. It is a question whether in large sizes there can be built any hand-regulating induction regulators that will cost much less than four dollars a kilowatt, at which to-day these large high-speed machines are actually being sold, and that makes a minimum cost of a high-speed machine about 40 per cent. of the cost of the ordinary-type machine, rather than 60 per cent. The general question is an exceedingly important one, taken in conjunction with the fact that it is possible by the use of these synchronous condensers, especially when connected with direct-current machines, to automatically compound; the same automatic compound may be produced through the exciter by means of the Tirrell regulator or some other regulator of this form. And when we get away from the difficulty and the inaccuracy of hand regulation, we have overcome the most serious objection that has been raised in any of the discussions on the employment of the synchronous condenser.

F. O. BLACKWELL: In connection with what Dr. Perrine has just said, the speaker would say that it is possible to put an automatic field regulator on a rotary condenser which will make it maintain constant pressure in the sub-station notwithstanding variations in speed and pressure in the power-house. To carry this idea still further, a fly-wheel can be added to the rotary condenser which will steady the plant by absorbing and giving out energy when the load fluctuates. This has been done in Germany on a considerable scale where large hoists are operated by motor-generator sets with fly-wheels. The steam-turbine alternator is well adapted to be used as a rotary condenser where steam power is auxiliary to a long-distance transmission water-power plant. Its fly-wheel capacity is large and the friction of a steam-turbine, particularly if it is mounted on a vertical shaft, is extremely small.

RALPH D. MERSHON: The speaker wishes to take issue with Mr. Waters on his statement that Mr. Lamme has over-estimated the value of the inherent regulation of the motor. Even if the regulation of pressure is, as Mr. Waters says, a matter of hand regulation, still the measure of effectiveness of this hand regulation is the extreme regulation possible, the regulation from full load to no load. The less the extreme variation is, the better the regulation, whether it be manual or automatic. Mr. Lamme has brought out the conditions in the design of the synchronous motor that are necessary for such regulation, and it is the opinion of the speaker that he has not laid any too much stress on it.

The paper by Mr. Lincoln to which Mr. Waters also refers stated the limitations and the amount of power that could be transmitted over a line at different frequencies with a given limitation in the amount of drop. He took the drop at 20 per cent. Now if you take a given drop as the limitation, then Mr. Lamme's contention is an extremely interesting and important one.

The *extreme regulation* of any system; that is, its regulation from full load to no load, is a measure of its regulation for any change of load, since the change of pressure for any change of load, large or small, is proportional to the extreme regulation. Therefore, whether the regulation of a system be automatic or manual, the extreme regulation is of importance. The extreme regulation may or may not be identical with the total drop in the system.

In a circuit feeding its load direct without the aid of corrective synchronous motors, the extreme regulation and the total drop are identical. Hence the regulation; that is, the variation of the delivered pressure varies as the load varies, is measured by the total drop. But if synchronous motors be used to control the power-factor the total drop is not necessarily the same as the extreme regulation and therefore not necessarily a measure of the regulation. Whether or not it is a measure

depends upon the characteristics of the motors used. If the motors have in them, when delivering a leading current to the system (= a lagging current in the motors themselves) a drop equal to that of the transmission, then the extreme regulation will be just equal to the drop so that the total drop is a measure of the regulation. If the drop in the motors when delivering leading current is greater than that of the transmission, then the extreme regulation of the system will be greater than the total drop of the transmission and the regulation worse than the total drop would indicate. If the drop in the synchronous motors is less than that of the transmission, then the extreme regulation of the system will be less than the total drop in the transmission and the regulation better than the total drop would indicate.

Since, with a given drop, in a long transmission having a lagging power-factor, a limit is soon reached in the amount of power which can be transmitted, it is desirable in long transmissions to use corrective synchronous motors. The use of such motors is also advisable from the fact that by reducing the transmission current they reduce the transmission loss. From what has been said it is clear that the regulation of such a system will be largely dependent upon the regulating qualities which the corrective motors have when a lagging current is being drawn from them. The subject of the regulation of such motors under such conditions is therefore of very considerable importance, and Mr. Lamme has, in the opinion of the speaker, rightly laid great stress upon it.

S. B. STORER: Mr. Waters has taken exception to Mr. Lamme's reference to the use of the squirrel-cage induction motor. The speaker is more inclined to agree with Mr. Lamme than with Mr. Waters, as the resistance of the squirrel-cage winding would seem to be considerably less than that indicated by Mr. Waters' remarks. Mr. Waters says that in this form of secondary there is from six to seven times the resistance of that of the armature type of induction motor secondary. If that is the case then the squirrel-cage winding would drop below synchronous speed from six to seven times as much as the other type of winding. General practice does not show this to be true.

On a large motor with the squirrel-cage secondary the regulation in speed is two to four per cent., and if the resistance of that secondary were six or seven times the resistance of the motor having the regular armature type secondary winding then the slip of the latter would be one-sixth as much, or only a fraction of one per cent. General practice does not show this to be true either.

CHAS. F. SCOTT: This subject, involving as it does synchronous apparatus for adjustment of regulation and power-factor, is one which seems more or less confused. In considering questions of this kind the speaker has a method of

analysis which is quite simple and straightforward. It involves a physical rather than a mathematical analysis of these problems, and it may be well to give it here.

In an alternating-current system one may consider that two things are being generated; power and electromotive force. The system receives its power through the shafts of its generators, either from water-wheels or engines (for convenience we shall simply refer to engines). The system receives its electromotive force through the magnetic field produced by the field magnets of the generator. The greater the field strength the greater also is the electromotive force. The field magnets for supplying the electromotive force correspond in a way, therefore, to the engines which supply power.

A power-house may contain two similar outfits, both driven by similar engines and supplying equal power to the system. Furthermore, both of the generators supply electromotive force and have field magnets and equal field magnetizing currents and supply equal electromotive forces to the system. If the two outfits are running in parallel and the power be shut off from one of the engines, then the system will receive power from one outfit, but electromotive force from both. The drop in electromotive force on change of load will not be determined by the joint action of a single machine but of the two machines. Therefore the regulation will be much closer with the two generators in multiple and will be essentially the same whether power is received from one engine or from two.

If one of the machines be transferred from the power-house to a distant sub-station there remains the same capacity for generating the electromotive force as there was when the two machines were close together. There is a difference, however, in that one of the generators is now located at the point of distribution so that it is a generator of electromotive force close to the point of distribution without interference of line losses in the circuit from the power-house. There is thus seen to be a close similarity in the action of two generators running side by side in parallel and one generator operating a synchronous motor at a distant point in so far as the generation of electromotive force is concerned.

In Mr. Lamme's paper it is shown that the better the regulating characteristics of the machine, or in other words, the greater the effectiveness of its field, the more effective it is for its purposes. If we follow through the paper and note the different characteristics desirable in the machine, and if we further consider the various points brought out in the discussion we shall find that they may all be comprehended in a clear and definite way by simply assuming that we have transferred a generator from the power-house to a distant point upon the line where the electromotive force is needed and where it may be more effectively generated than in the power-house. There is nothing mysterious in the fact that a syn-

chronous motor is used. If it were not for the line losses it would be better to generate all the electromotive force in the power-house in the power generator. In general it is cheaper and more effective to provide generators with the desired field strength and regulating qualities rather than to provide other synchronous machines for generating the electromotive force. The reason that it is sometimes preferable to use the auxiliary synchronous machine lies in the fact that it may be placed near the load, and therefore generate the electromotive force where it is needed.

In considering the second division of the paper, namely, that relating to the control of the power-factor of the circuit, we may follow the same line of reasoning. In our electric system we may consider that we are generating currents of two kinds; one a current in phase with the electromotive force; the other a wattless current having a phase relation of 90° to the former. Ordinarily these two currents are produced in the same armature and combine to give a resultant at some intermediate angle dependent upon the relative values of the two currents, upon which in turn the power-factor is dependent.

If, again, we consider that a power-house has two generators, we know that the two could supply equal power and equal current at the same power-factor. On the other hand, adjustments could be made so that one of the generators will supply all of the working current of the circuit at 100% power-factor while the other supplies the wattless current. In this case the engine of the second generator would do no work and it might be disconnected from its generator. In general, however, as pointed out in the original paper, this is not a good thing to do, because the two kinds of current can be generated in one armature more economically than in two armatures. For example, if the requirements of the circuit are that there be 70 amperes of each kind of current, then each armature must develop 70 amperes. The resultant of the current, however, is 100 amperes, so that one machine having a capacity of 100 amperes could give the same effective output as two machines each of 70 amperes. This shows the fallacy of the suggestion sometimes made, that a machine running idle should be installed in a power-house for supplying wattless current. It is much more economical to install a generator of sufficient size for supplying the necessary current. There may of course be exceptional conditions, where the generator is already installed, in which the best arrangement under the circumstances may be the installation of an auxiliary machine. When, however, there is a transmission line, it is obviously desirable to carry simply the power current for transmitting the necessary energy and not to impose the wattless current upon the transmission line. The wattless current is objectionable in the line for two reasons; it increases the total current to be carried, and it also very considerably increases

the drop in pressure in the line. If therefore the wattless current could be generated at the point where it is needed; that is, at the point of distribution, the transmission line will be very greatly relieved and its capacity increased. In a sense therefore we are simply relieving the transmission line from carrying wattless current and putting the generator for producing this current at the sub-station near the load.

If the various points taken up in the original paper relating to the desirable characteristics of the machine and also the points brought out in the discussion are considered, we shall find that the various requirements are quite rational and that the purpose is simply to generate two currents, one a power current at the power-house and the other a wattless current at the sub-station.

The synchronous machine at the sub-station can therefore accomplish both of the desired results. Namely, by supplying electromotive force it can facilitate the pressure regulation, and by supplying wattless current it can relieve the transmission line.

Many of the objections to synchronous motors for general use do not apply to the use of synchronous machines for the foregoing purposes. It is the speaker's opinion—which he thinks is coming to be the general opinion also—that a considerable number of synchronous motors of various sizes, particularly motors of small size, scattered over a system under the control of various operators, does not constitute a satisfactory working condition. In a theoretical way it may be all right and matters may run smoothly for a time, but when an accident occurs at one place trouble is very likely to occur in many places, resulting in interruption to service.

The induction motor is the simple one for the general distribution of power. In those cases where the magnetizing or wattless current taken by it cannot well be provided by the generating and transmission system, as is sometimes the case in long-distance lines, this current may be supplied by large synchronous machines running in sub-stations. When large machines are operated in stations so that the machines themselves are few and the operators are intelligent and skilled men, then objections to the synchronous operations are reduced to a minimum and the operation is comparable to the ordinary synchronous converter sub-station which has demonstrated itself to be quite practicable.

Even this statement does not imply that all large motors should be synchronous motors. The large induction motor has a relatively high power-factor, and the operating simplicity of this motor and the characteristics of its speed-torque curve make it in many cases much preferable to the synchronous motor.

The use of one machine which may sometimes be driven by an engine at the sub-station and at other times as a pressure regu-

lator, has been mentioned once or twice in the discussion. A case came to the speaker's attention some time ago in which such an arrangement seemed to be advisable from the standpoint of the customer. The customer was intending to purchase a considerable amount of power from a transmission system, and his proposed contract was based on power furnished at a certain power-factor. If the power-factor was lower the rate was to be increased, and if the power-factor was higher the rate was to be decreased, and the immediate problem was whether the increase of power-factor which could be secured through the use of an auxiliary synchronous machine would make it worth while to make arrangements so that the machine could run part of the time as an idle synchronous motor and part of the time as a generator driven by an engine. It was proposed to install the engine for a relay in cases of emergency. The synchronous machine would therefore be so arranged that it could be used as a generator of wattless current for raising the power-factor under ordinary conditions and as a power generator in cases of interruption to the outside service.

The speaker is inclined to think that this general method of operation is applicable to long distances and larger powers, and that it will not be found expedient to introduce it in smaller plants on account of the extra complications which may more than compensate for the advantages and expense involved.

F. A. C. PERRINE: Will Mr. Scott please say if it is a correct corollary to the first part of his remarks to state that in case of long-distance transmission plant generating at about five cents per kilowatt-hour, what is a fair figure for such plants transmitting to long distances? Would it be correct to state that it were better to use a steam-driven generator for regulating the pressure—power from the steam-driven generator costing about one cent per kilowatt hour—or a synchronous motor?

CHAS. F. SCOTT: Of course special cases will admit of almost anything, but the speaker did not have in mind the supply of mechanical energy at the sub-station simply to assist in either the regulation of current or pressure. That would not be necessary in general, unless the speed were the real factor which needs correction and regulation. There may be cases in which the fluctuations in load would cause fluctuations of speed in a water-wheel that a steam-engine would be a good adjunct as a speed regulator. But the speaker has not had in mind the introduction of power from a steam-engine simply to assist the control of the pressure or the current.

J. S. PECK: There is an interesting bit of history connected with this system of adjusting power-factor by means of a synchronous motor. About 1890, Mr. Lamme did a considerable amount of experimental work along this line, with a view of determining the extent to which the pressure of a generator could be varied by changing the field strength of a synchronous

motor which was supplied from it. Experiments were carried on for a year or two in order to determine definitely what could be done, and in 1893 an application was made for a patent covering this system of operation. The patent was, however, refused by the Patent Examiner, on the ground that a current could not lead the pressure which produced it. About one year later, a patent was granted to another engineer covering substantially the same arrangement. The matter was called to the attention of the Patent Office officials, and after a time Mr. Lamme's original patent application was granted.

A perusal of this Patent Specification shows that as early as 1893 Mr. Lamme had a clear conception of the action of synchronous apparatus in controlling the power-factor and pressure of an alternating-current system, as well as the reasons why the various results were obtained. Although the specification was written more than ten years ago, practically all the essential points which have been brought up to-day were covered therein.

Dr. Perrine expresses surprise at the fact that Mr. Lamme says that the cost of a synchronous motor regulator will be from 60% to 80% of the cost of an alternating-current generator of the same capacity and of ordinary speeds. The relative costs given by Mr. Lamme are based on equal currents on short circuit. Mr. Lamme calls attention to the fact that high-speed turbo-generators, of which the cost per kilowatt is comparatively low, are usually designed to give less current on short circuit than generators operated at the usual speeds. Regarding the superior regulating action of the motor supplied with dampers on the poles, Mr. Lamme refers to momentary effects only.

S. B. Storer: In connection with the use of synchronous regulators, one point has not been referred to; that is, the effect in case of a short circuit in a very large system where synchronous regulators are used for maintaining a very high power-factor. The present tendency is to limit the short-circuit of all large plants to as small an amount as possible consistent with fair regulation. It seems to the speaker that with the general use of these synchronous regulators in sub-stations the short-circuit current which might be obtained at a given point would be so much larger than where induction regulators are used, that it will be very difficult to overcome and will prove an objection to their use.

H. W. Buck (*by letter*): Mr. Lamme's paper shows the important functions which a synchronous motor can perform upon a power transmission system. The writer should be inclined to go further and say that synchronous machinery of some kind is a necessity on almost every power system, where alternating current is distributed, as a compensator for lagging currents.

If the power is used by a large number of small consumers,

as is frequently the condition, the majority of these users will install induction motors, both on account of the simplicity of the type, and also because their conditions of operation require frequent stopping and starting and high torque on starting, which conditions exclude the use of motors of the synchronous type. While it may be argued that large modern induction motors with small air-gaps have high power-factors at full load, many of the motors on the average power system may not be very large, and they are seldom running at full load. Their power-factors at fractional loads will be much less. Over the entire system there will be perhaps hundreds of induction motors, some of them running light, many of them running at about half load or less, and only a few operating at the exact load at which the high guaranteed power-factor can be obtained.

The result of this condition is, in the experience of the writer, that the average power-factor on such circuits at normal loads is not over 70%, and frequently it falls as low as 60%. Such a condition is, of course, highly objectionable. This increased current, which earns no revenue but which simply causes heating and excessive "drops" all along the line, will so enlarge the investment in generating and transmitting apparatus that the profits from the business may be seriously impaired.

If the electrostatic capacity of the transmission system is high, compared with the amount of power transmitted, as is the condition in some very long-distance high-pressure systems, the charging current of the line may offset the magnetizing currents of the induction motors and no other source of leading current is required. In a distribution such as that from Niagara to Buffalo, however, where the transmission pressure is comparatively low, and the induction motor load very large, the corrective effect of the line-charging current is negligible, and some source of leading current is essential.

Condensers as now constructed are expensive and bulky, and are practically out of the question for commercial frequencies. Synchronous apparatus, then, is the only possible source of the required leading current, and their installation should be insisted upon by the distributing company in every case where the users' conditions will permit. Arrangements can usually be made with the customer to operate such motors with leading current; if not, they can certainly be operated at unity power-factor, so at least they will not add any *lagging* current to the system.

Synchronous converters will of course answer the same purpose, but their armatures will not allow as much leading current as a synchronous motor, on account of heating. It may be of interest to note here that if the single-phase railway becomes the standard system of the future, the railway synchronous converters now so commonly used on power systems for phase control, will disappear, and the lagging currents in the single-phase motors will be added. Synchronous motors as sources of leading current will then be needed all the more.

There is a general feeling that a synchronous motor cannot be used in any installation where torque is required to bring the plant up to speed, and that in general a synchronous motor is a very difficult machine to start. Synchronous motors are now designed with a considerable starting torque, and with such characteristics that they will come up to synchronism very promptly without taking more than 25% in excess of full-load current. A suitable starting device is of course required. If very high starting torque is required, friction-clutches can be installed between the motor shaft and the work, which can be thrown in after the motor is up to speed with its field on, when the full torque can be obtained. There is a 500 h.p. synchronous motor on the Buffalo system, which is started in this way, with a clutch, and the operation is perfectly satisfactory. The clutch surface is well greased and thrown in gradually, and the entire plant, which is a flour-mill with all its multiplicity of belts, counter-shafting, grinders and other machinery, is brought up to full speed in a very short time without exceeding full-load current.

Another important function of synchronous motors on a system (aside from their ability to steady the pressure as mentioned by Mr. Lamme) lies in the fact that they act to steady the frequency. Since the synchronous motors are rigidly connected to the power-house generators by an electromagnetic coupling, their fly-wheel effect is added directly to the generator fly-wheel effect, and consequently they aid the generating units in the maintenance of constant speed. Induction motors cannot so operate. Their connection with the generators on the system is loose, so to speak, there being a lost motion lying between the positive slip of the motor, operating as a motor, and the negative slip which must exist in the motor before its fly-wheel effect can react on a falling generator speed.

The above stated advantages of the synchronous apparatus assume that ideal conditions exist on the system for the effective use of the characteristics of this type of machine. There are, however, circumstances under which the theoretical benefits cannot be realized. One is in the case where pulsations are impressed upon the system such as almost always result where the prime mover is a reciprocating engine. These pulsations, however small they may be, under certain conditions seem to disturb the balance of the synchronous machine, and it is practically impossible to obtain any satisfactory phase control by field adjustment, on account of hunting or other cumulative action.

Another troublesome condition is met where a synchronous motor is installed on a system of large electrostatic capacity when the counter e.m.f. wave of the synchronous machine is widely different from that impressed by the generators. Here a large current may flow in the motor armature, the frequency of which will be that of the harmonic which has distorted the

motor's counter e.m.f. wave. This current will flow back into the line as a charging current, and the motor may have more than full-load current in its armature, regardless of load and field adjustment, and phase control is impracticable.

T. J. JOHNSTON (*by letter*): Mr. Lamme's paper on the use of synchronous motors for regulation of power-factor in transmission lines is most timely. Mr. Lamme does not suggest any means of varying the reactive effect of the motor to compensate for variations on the line; it is manifest that fixed conditions do not prevail upon a transmission line, where at one time numbers of converters are in use, and at other times some or all are shut down; or where many induction motors are used as a day load and at night the principal service is incandescent lighting, or lighting with constant-current transformers. Under such conditions the power-factor of the line as a whole changes, and sometimes quite rapidly, so that manual regulation of a resistance in the field-circuit of the motor does not entirely fit the situation. The proposal which the writer made as long ago as 1901 to solve this difficulty was separately to excite the motor and feed the armature of the exciter (which should be on the same shaft with the motor armature) with alternating current from the main line; a connection being made from one armature to the other in such manner that the polarities induced in the exciter armature by the main alternating current are somewhat in advance of those due to its rotation across the field-magnet poles, and of the same sign.

With this arrangement when the main line current leads, the magnetic maxima in the exciter armature pull apart and the resultant magnetization is decreased so that the pressure and the exciter current drop, thus lowering the field magnetism of the motor; conversely, when the main line current lags, or leads to a less extent, the magnetic maxima approach each other, and the resultant pressure of the exciter is raised. This arrangement gives with a magnetic circuit having a good deal of iron a practically incremental regulation of the power-factor. Its resemblance to Mr. Rice's method of regulating the pressure of an alternating generator will of course be observed; the difference, however, is that in case of a generator the power-factor is not regulated at all, but the inductive reactance is compensated by an increase of the terminal pressure of the generator, and consequently of its output; whereas in the scheme now proposed the pressure differences are substantially unaffected.

It was a surprise to learn that motors of such large output were contemplated by Mr. Lamme for regulation alone, and perhaps it will be a surprise to many engineers more familiar with the problem. The proposed speed of 3600 rev. per min. seems prohibitive. An inductor alternator of 3000 rev. per min. within the writer's knowledge gave enormous trouble in bal-

ancing, and when at its best could be heard half a mile; the diameter of the inductor was not substantially different from that of a synchronous motor of the sizes proposed.

Not much could be accomplished by the use at only one end of the line of the regulation here suggested. Theoretically the compensation for inductive or capacity reactance must be infinitely distributed; and following the principles laid down in Chapter XII. of Dr. Steinmetz's *Alternating Current Phenomena*, it will be necessary to install these regulators at a number of points on any long transmission line; of course, under such circumstances the sizes contemplated could be reduced. For example, in those transmission lines from which branch several side circuits to different points, a regulator might be installed at or near each junction of the main line and a branch, to take care of the power-factor regulation. The power-factors at different points on a long line often differ appreciably.

The synchronous converter is not well adapted for this purpose, not only for the reasons pointed out by Mr. Lamme, but because of the danger of reversal with such a machine, causing it to operate from the continuous-current side if the inductive compensation is carried too far. This would necessitate special arrangements to prevent the converter racing, and render it difficult to operate in multiple with others; laying aside the question of hunting when the continuous-current load changes.

There ought to be a future for this form of regulator, not only on transmission lines as ordinarily understood, but in alternating-current railway practice. With proper design and output proportioned to the work, there seems no reason why these comparatively simple machines might not be installed and require only a minimum of attention.

A paper presented at the 188th Meeting of the American Institute of Electrical Engineers, Chicago, June 21–22, 1904.

Copyright, 1904, by A. I. E. E.

LONG SPANS FOR TRANSMISSION LINES.

BY F. O. BLACKWELL.

Many cities to-day are dependent for their lighting, transportation, water supply, and the operation of their industries upon electric power transmitted over considerable distances.

Unfortunately interruptions of the power service do occur not infrequently and when they do happen they so inconvenience the public as to be most conspicuous. The impression that long-distance power transmissions are unreliable has some basis of fact that seriously interferes with their development. Although absolutely continuous service may not be possible, many of the troubles now experienced can be either altogether eliminated or greatly reduced. Among the principal causes of interruption, so far as the line is concerned, may be mentioned:

Short circuiting of lines by branches of trees, wires, or by large birds getting across them.

Burning of wooden pins, cross-arms, and pole-tops by leakage or electrostatic discharges from the conductors.

Burning of wooden poles at the ground from forest or prairie fires.

Failure of insulators from puncture by the current, or their destruction by missiles, discharged maliciously.

Lightning damaging the apparatus connected to the circuits and sometimes destroying poles.

Accidents due to heavy winds overturning the poles or to floods washing them out.

The deterioration of a line requires its replacement in from five to twenty years, depending on climatic conditions and the material which is used in its construction. This replace-

ment of the poles with new ones can only be done by shutting off the current or at the risk of accidental interruptions.

Let us see what can be gained by substituting a steel tower construction with long spans for a wooden pole line. Short circuits are by far the most common difficulty, the only remedy for which is to put the wires so far apart that they are unlikely to be bridged across. This can readily be done even with more than one circuit when a steel cross-arm is employed. Burning is of course entirely done away with where metal construction is used.

Failure of insulators from electrical causes can be obviated by getting larger and better insulators; this is practicable where the spans are long and the number of insulators is small. Insulators on high towers are much poorer targets than when they are near the ground and so are less liable to be broken.

Each metal tower is a lightning-arrester and as they are the highest points in the line they materially assist in its discharge; the tower itself, being a conductor, cannot be injured by lightning. Steel structures can be exactly figured to meet safely any strains that can come upon them and can generally be located only at safe places where there is no danger of washouts. The deterioration of a properly constructed and well-galvanized steel tower is very slight, as is proved by marine and windmill experience, and is practically negligible so far as the pins and cross-arms are concerned. Any part of a steel tower can be readily removed and replaced without interrupting the service.

By far the greatest gain obtained from long spans is in the reduction of the number of parts. If one insulating support takes the place of four or five, line troubles will be reduced nearly in direct proportion; the inspection and repair of the line will be much simplified and its cost of maintenance correspondingly diminished.

Cost of Towers.

The cost of a tower construction as compared with wooden poles depends on the locality. Where the right kind of timber exists, it is of course cheaper; but in tropical countries where wooden poles would have to be transported long distances the towers are much less expensive. In addition, to obtain long life a creosoted wood only could be employed and this still further increases the expense. The fewer insulators and pins and the ease of transportation and erection are in favor of towers. They can be packed in light bundles suitable

for mule-back transportation and quickly put together even in the most inaccessible places. Even where the cost of the tower construction is more it is often justified by the greater certainty of operation which it insures and the lower cost of maintenance.

Strength of Conductor.

The first and most important consideration for long spans is the material of the conductor. Copper, aluminum, and iron are availiable for this purpose. Various alloys of copper have great strength, but their conductivity is too low and their cost too high to compare favorably with the more common metals. Copper wire varies widely in its characteristics, depending on the methods used in its manufacture. The copper is received at the wire-mill in the form of cast-wire bars weighing 300 to 350 lb. It is then rolled into rods and the rods are drawn into wire of the required size. The temperature at which the metal is rolled, the reduction of area both in rolling and drawing, and the amount of annealing which the wire is given—all have an important bearing on its characteristics. As the size of the original wire bar is limited, the smaller the wire the more it is worked and in general the better the result.

Cable made up of several strands has the advantage of using smaller wires than a solid conductor, and also permits of longer lengths of conductor without splices. Assuming a 300-lb. wire bar, a 19-strand cable, for example, can be made up weighing 5700 lb. while if solid wire were used the weight of one piece would be 300 lb. In other words, there would be 19 times as many joints with the solid wire as with the 19-strand cable. The smaller the wire and the greater the strength, the more brittle it becomes. This is partly compensated for by the greater flexibility of a cable and the fact that a strand can break without the whole conductor parting.

Each strand should be a continuous wire without joints. Joints in the cable should be as few as possible and made by means of sleeves, as brazing or soldering anneals the wire and much reduces its strength. The permissible tension in the cable must not exceed the elastic limit, by which is meant the point at which the material will continue to elongate and will eventually break, and not the usually accepted meaning of elastic limit as that point at which the strain ceases to be proportional to the stress. Copper cable recently made for a transmission plant with spans of 500 feet had an elastic limit of 40 000 lb.

per square inch; similar aluminum cable had an elastic limit of 12 000 to 14 000 lb. per square inch; galvanized-iron telegraph wire has an elastic limit of 35 000 lb. The ultimate tensile strengths of these wires were 60 000 lb. for copper, 24 000 lb. for aluminum, and 55 000 lb. for iron.

The advantage of aluminum is that it weighs less than copper for the same conductivity, but for long spans its lesser strength, greater diameter, and higher coefficient of expansion are against it. Steel wire has about nine times and iron wire or cable about six times the resistance of copper so that they are more expensive as a conductor than copper. In order to avoid oxidization it is necessary to galvanize iron or steel wire; which partly anneals it and reduces its strength. There are cases where the size of high-pressure line conductors is determined not by resistance but by mechanical strength, and in such cases iron or steel wire can be used to advantage.

Elasticity.

The elasticity of the conductor is of considerable value in reducing the sag when the stress is removed, as will be shown later. The elongation of the wire under stress is less after it has once been stretched. The elasticity of cable is greater than that of solid wire, but both wire and cable take a set under any stress to which they may be subjected. In the following table is given the modulus of elasticity of copper, aluminum and iron wire.

Copper hard-drawn wire	19 500 000
Aluminum hard-drawn wire	10 200 000
Iron telegraph wire	24 000 000
Copper hard-drawn cable wire	16 300 000

Each sample was stretched to a point somewhat below its elastic limit before testing. It will be noted that the copper cable is considerably more elastic than the solid copper wire, the latter being a strand of the cable. The aluminum wire was of nearly the same conductivity as the copper-wire strand and presumably would have had a lower modulus of elasticity if made up into cable. Aluminum is considerably more eaastic and has a decided advantage over copper in this respect.

Coefficient of Expansion.

The coefficients of expansion for Fahrenheit degrees are as follows:

Copper	0.0000096
Aluminum	0.0000130
Steel	0.0000064

As the worst condition so far as sag is concerned is reached when the conductor is hot, a low temperature expansion is most desirable for long spans, and steel is in this respect better than either copper or aluminum.

Strains in Conductors.

The strains upon the conductor are those due to its own weight and the wind acting upon its surface. In a cold climate in addition sleet may form upon the wire, increasing the weight and the surface exposed to the wind. On a line carrying any considerable amount of power it is improbable that sleet will ever form, the formation being prevented by heat due to losses in the conductor. In order to be on the safe side, however, it is best to assume in the North a coating of ice one inch thick all around the conductor. The wind velocity could never exceed 100 miles an hour which would give a pressure of 40 lb. per square foot on a flat surface, or 20 lb. on a cylindrical surface such as that of a wire. The weight is of course a vertical stress and the wind a horizontal one at right angles to the wire. The greatest strain is caused by the resultant of these two. The worst conceivable condition is sleet on the wire, followed by extreme cold weather with high winds. Under such conditions the probabilities are that the ice on the conductor would break off, but without some data on the subject it is hardly safe to assume that this would be the case. In warm climates the absence of sleet and the lesser range of temperature make permissible longer spans than in cold climates.

Sag of Wire.

The maximum sag may be due to the conductor being loaded with sleet or to heating of the wire in a hot sun. The latter will generally be found to give the greater sag. Owing to the conductor being elastic it is not necessary to consider the greatest deflection from a horizontal line between supports as the vertical sag of the wire. The wind pressure causes the wire to swing to one side and it is elongated by the combined strain of wind and weight, but as soon as it is relieved of the wind pressure it swings back to a vertical position and contracts to the length required to carry its weight alone. The sag due to heating of the wire is also somewhat less than it otherwise would be, because when expanded the strain is less and the wire contracts.

The extreme variation of the temperature of the air in cold climates is about 150° fahr., while farther south it does not exceed 100° fahr. To this must be added something for a metal con-

ductor exposed to a hot sun. There are no data upon this but a total variation in the temperature of the conductor of 175° fahr. should be sufficient in any country.

Span and Sag Curves.

The attached curves of span and sag are based on the following data:

	Aluminum	Copper
Area 6-strand cable	0.21 sq. in.	0.132 sq. in.
Diameter 6-strand cable	0.59 in.	0.51 in.
Weight per foot	0.240 lb.	0.509 lb.
Elastic limit	12 000 lb.	40 000 lb.

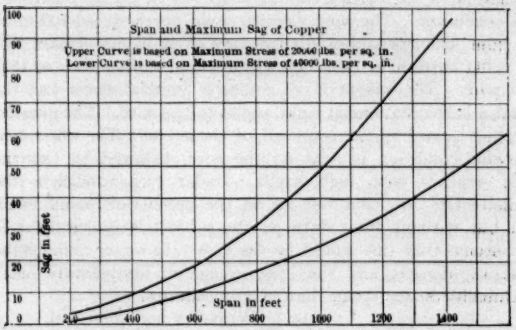


Fig. 1.

Stress at 1/2 elastic limit	1267 lb.	2640 lb.
Stress at elastic limit	2534 lb.	5280 lb.
Wind pressure per sq. ft.	40 lb.	40 lb.
Wind pressure per ft. cable	0.98 lb.	0.84 lb.
Coefficient of expansion	0.000013	0.0000096
Variation in temperature	150° fahr.	150° fahr.
Modulus of elasticity	8 000 000	16 000 000

The equations from which the curves were calculated are given below and alongside of them is an example of a 1000-ft. copper span.

$$D = \frac{S^2 \times W}{8\,T} = \frac{1000^2 \times 0.98}{8 \times 2640} = 46.4 \text{ ft.}$$

In which D = deflection in ft.

S = span in ft.

W = resultant of weight and wind in lb. per ft. of cable

and T = stress allowed in cable in lb.

$$L = S + \frac{8\,D^2}{3\,S} = 1000 + \frac{8\times 46.4^2}{3\times 1000} = 1005.74 \text{ ft.}$$

In which L = length of cable, cold.

$$L_0 = \frac{L}{1+\frac{F}{E}} = \frac{1005.74}{1+\frac{20\,000}{16\,000\,000}} = 1004.38 \text{ ft.}$$

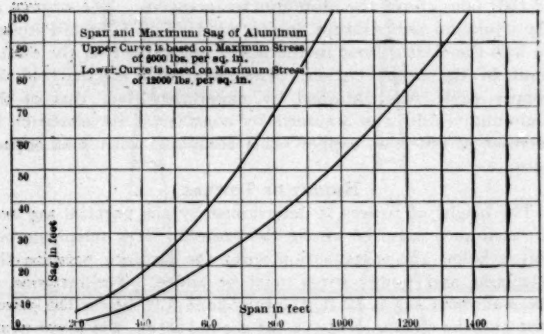


FIG. 2.

In which L_0 = length of cable without stress

F = lb. per sq. in. permitted in cable

and E = modulus of elasticity

$L_H = L_0(1+C\,B) = 1004.38\ (1+0.000009\times 150) = 1005.81$ ft.

In which L_H = length of cable, hot (150° fahr. rise in temperature)

C = coefficient of expansion

and B = maximum degrees F. rise in temperature

$$D^3 + \frac{3\,S}{8}(S - L_H)\,D = \frac{3\,S^3\,L_H\,W}{64\,E\,A}$$

$$D^3 + \frac{3\times 1000}{8}(1000 - 1005.81)\,D = \frac{3\times 1000^3\times 1005.81\ W}{64\times 16\,000\,000\times 0.132}$$

$$D^3 - 2178.7\,D = 22323\,W$$

In which A = area of cable.

From this equation any deflection of the cable can be assumed and the corresponding weight calculated. For instance, in the example if $D = 48.8$ ft., $W = 0.51$ lb.; that is, the sag hot without wind is 48.8 ft., and this is the maximum vertical deflection under the conditions assumed.

If $D = 51.1$ ft., $W = 0.98$ lb. which is the maximum deflection with wind but this is at an angle of 31° from the horizontal and the vertical sag is only 26.6 ft.

The curves (Figs. 1 and 2) give the maximum sag for copper and aluminum cables at different spans with an increase of temperature of 150° fahr. above the minimum temperature. The stresses at the minimum temperature due to wind and weight are limited to half the elastic limit in the upper curves and to the elastic limit in the lower curves. The modulus of elasticity of the copper cable was obtained by experiment, but that of the aluminum cable was assumed by considering its elasticity to increase as much as copper cable compared with solid copper wire.

Height of Towers.

The height of towers is determined by the vertical sag and the clearance required above the ground. If a telephone circuit is below the transmission wires the distance between the telephone and power wires must be added. For instance, if the maximum sag is 12 ft. the telephone 6 ft. below the power wire and the clearance above the ground 20 ft., the tower must evidently support the wires 38 ft. from the ground.

Insulators and Pins.

The insulators and pins must have sufficient mechanical strength to bear the strain transmitted to them from the cable. For example, in the 1000-ft. span just figured on the strain would be 980 lb. per insulator 31° from the horizontal. A properly-designed porcelain insulator will stand any strain that the pin will bear without bending. A rigid cast-iron or steel pin is therefore essential and can readily be obtained.

The Cross-Arms.

The cross-arm is of course subjected as a beam to the weight and wind strains transferred to it from the cable, but in addition there is a torsional strain due to the breaking of a conductor that can best be borne by a pipe. The length of the cross-arm should be sufficient to space the wires well apart and prevent

short circuits either from objects thrown over the line or from the wires swinging together. The former is the more important and if a safe distance apart, say six feet, is chosen it will be sufficient to guard against the latter, as on short spans with relatively less distance between wires they invariably swing together and never touch each other.

CONSTRUCTION OF TOWERS.

The most economical tower construction is one in which the

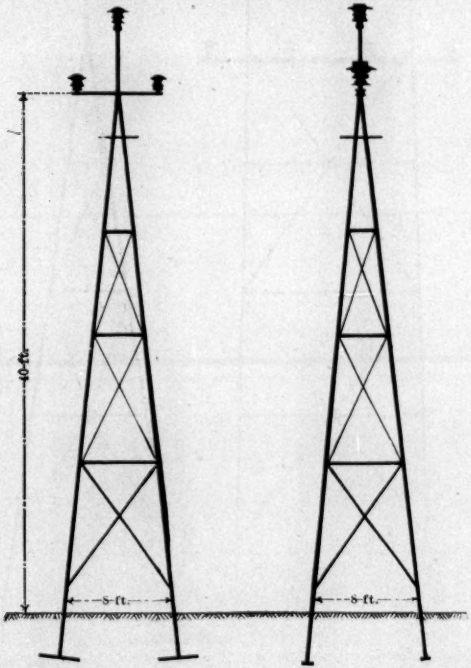


FIG. 3—Single circuit tower used with 448 ft. spans for the Guanajuato Power and Electric Co. of Mexico.

spread of the legs at the ground is about one quarter to one third the height of the tower. If a less spread is used, the

weight of the legs becomes excessive and with a greater spread the cross-bracing must be much increased in size. For a single circuit the common windmill tower construction in which the legs are locked together at the top has the advantage of reducing the strains to a simple compression of the legs on one side and

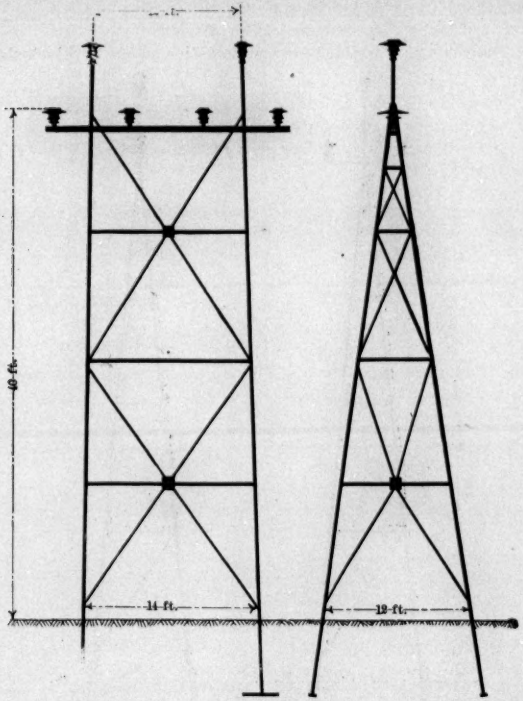


FIG. 4.—Double circuit tower used with 440 ft. spans for the Guanajuato Power and Electric Co. of Mexico.

tension on the other, the only function of the cross-bracing being to prevent the legs buckling when in compression.

Where there are two or more circuits the length of the cross-arm is so great as to require two points of support. The tower

can then be made with a width at the top approximating that at the bottom and the cross-bracing has to bear its full share of the lateral strains. A truss construction with the fewest number of parts and opportunities for slack motion and racking of the tower is preferable. Spreading the legs far apart obviates the necessity for expensive concrete foundations, as the strains can be made well within the limits which earth will stand in compression and the weight of earth above the foot of the tower is sufficient to prevent its pulling out of the ground. A heavy galvanizing coating on the tower appears to be an effective protection against rusting and avoids the expense of painting.

Fig. 3 shows the construction employed in the transmission of 101 miles from Zamora to Guanajuato, Mexico, which was the first transmission employing steel towers exclusively. The towers were spaced 440 ft. apart and are designed for a single circuit.

Fig. 4 shows the tower which will be used for the transmission of 90 miles from Necaxa to the City of Mexico, and 170 miles from Necaxa to El Oro, Mexico. These towers will be spaced 500 ft. apart with occasional spans running up to 1000 ft.

The same tower will be used for the transmission of 90 miles from Niagara Falls to Toronto but the distance apart will in the latter case be 400 ft. on account of the possibility of sleet accumulating on the conduotors. There will be two circuits or six wires on each tower and in both the Necaxa and Niagara Falls transmissions noted above there will be two lines of towers making four parallel circuits altogether.

This paper has been intentionally confined to the mechanical construction of transmission lines which the writer believes is more important now than the electrical side. To-day the highest pressure employed is 60 000 volts and the longest transmission 150 miles. There is nothing to prevent the use of higher pressures and longer transmissions, provided reliability can be obtained by a more permanent, substantial, and simpler construction even if the expense is greater. The use of long spans and metal construction is a most important step in the right direction.

BLANK
PAGE

DISCUSSION ON "LONG SPANS FOR TRANSMISSION LINES."

RALPH D. MERSHON: At the bottom of page 511 Mr Blackwell says: "The deterioration of a line requires its replacement in from five to twenty years." Presumably Mr. Blackwell refers only to the structure supporting the line. His statement would not hold true regarding the conductors. Of course the whole line does not deteriorate in any such short length of time. On the next page he speaks of the steel tower acting as a lightning-arrester. A few days ago the speaker heard of one line which had been in operation for some time, the construction of this line being similar to that described by Mr. Blackwell. Iron rods were attached to the tower and bent up around the insulator in order to protect it from a stroke by lightning. Has Mr. Blackwell ever seen a similar construction?

Mr. Blackwell also says: "If one insulating support takes the place of four or five, line troubles will be reduced nearly in direct proportion; the inspection and repair of the line will be much simplified and its cost of maintenance correspondingly diminished."

The speaker's experience with line troubles has been that of having less trouble from insulators than from any other part of the construction. Most of the trouble has been caused by forest fires burning the poles; trouble has also been caused by short-circuits due either to wire thrown over the line maliciously or by carelessness in the construction work for extensions, etc.

When a line is first put up, it is almost always the case that a number of the insulators are broken maliciously; after a little while, the insulators are let alone, even in the West. One transmission line with which the speaker was associated crossed a cattle ranch; the cowboys used the insulators for targets, shooting off as many of them as they could. In a short time, however, that practice was stopped, for that class of men, if you appeal to them in the right way, can be easily approached and reasoned with. One of the line inspectors brought the matter home to them by saying that the breaking of one of the insulators might mean the killing of a man at another place, a man who, after touching off a blast, was endeavoring to reach the surface by means of an electric hoist. In that particular case, where trouble of this kind was the worst that the speaker has ever known, it was stopped almost entirely.

On page 513 Mr. Blackwell says: "Permissible tension in the cable must not exceed the elastic limit, by which is meant the point at which the material will continue to elongate and will eventually break, and not the usually accepted meaning of elastic limit." Now what is the difference between what Mr. Blackwell defines there and the ultimate tensile strength which he speaks of on the next page?

There is another matter of importance mentioned by Mr. Blackwell; that is, if a line carries a considerable amount of

power, sleet is not so likely to form on the wire. This is especially true of high-pressure lines. With a given loss, the higher the pressure the smaller the conductor and consequently the greater the loss per unit of radiating surface of conductor, and, so far as the speaker has been able to observe, a small variation in temperature from that at which sleet forms will prevent its formation.

F. O. BLACKWELL: Answering Mr. Mershon's question; of course the deterioration on a line is confined to the wooden parts. Poles, under unfavorable conditions, may rot out in two years. In some places, as in India, ants eat up the poles. In dry ground, with the right kind of wood, the life of a pole may be 20 years. Mr. Mershon also refers to some trouble experienced at Guanajuato which was attributed to lightning. They have had some insulators break there, but, as the speaker understands it, they do not feel certain that the breakage was due to lightning. They are experimenting, however, with an extension of the tower to form a lightning-rod which they will place at exposed points on their transmission system.

Regarding the elastic limit of materials used for conductors, our experiments show that all of them, including copper, aluminum and iron, take a considerable set when subjected to any strain, and that the amount of this set depends on the time during which it is subjected to the strain. The cable is a sort of spiral spring. It is more elastic than a solid wire and its elasticity depends a great deal on the number of twists in the cable, the size of the hemp centre, and other conditions. We used a hemp centre because we found by experiment that a metallic core took the strain to which the cable was subjected before the outer strands and broke first. This made the cable with a conducting core weaker than one made with a hemp core.

Regarding sleet, it is probable that the only time when trouble would be experienced on a transmission of any size is when the power is off the line. At other times there will be sufficient heat generated in the wire to keep it above freezing point. In the case of this Guanajuata construction the insulators were cracked and split open. There was nothing in particular to indicate lightning; they were not burned except so far as they would be by short circuit from the line current.

A. S. HATCH: Possibly the experience of 20 years may be of interest in tower construction. In May, 1884, a windmill tower was erected for lighting a section of Detroit; it was triangular in cross-section, 22 feet on a side at the base and tapering to a point. There are nine 18-ft. gas-pipe sections, the first three being of 2.5 in., the middle three of 2 in. and the top three of 1.5 in., making the total height 161 feet. Weakness has been found to be buckling of the pipe standards, due principally to wind-strains. The towers have not been good lightning-arresters since switch-cases have been punctured after a storm. At the base of the towers are switches to control

the wiring, the cases of which were connected to the tower; and after a severe storm, a switch would be found punctured, showing the lightning had either left the line, jumping to the case of the switch and thence to ground, in case the ground is moist, or, as commonly the case, the lightning leaving the tower for the grounded line. The most common class of tower in use is also triangular but of uniform cross-section, and is built of 2-in. and 1.5-in. pipe, a section being 8 ft. high and 6 ft. on a side. The girts are 1-in. pipe and braced with $\frac{3}{8}$-in. diagonal stay-rods. The base of the tower is a single pipe 15 ft. high on which is a fitting to which both the horizontal and brace supports are fastened. The towers are guyed in four directions by two sets of guy-ropes consisting of 0.5-in. steel strand fastened to wooden stubs. These towers vary from 150 to 175 feet high, and on account of being used in a city are preferable, but the taper tower is better for transmission purposes on account of avoiding the use of stubs. There is no side-strain except that due to the line-wires fastened to the tower and sometimes having a span of 250 feet from a pole.

CHAS. F. SCOTT: The subject covered by Mr. Blackwell is a most timely and important one. It is notable that this paper deals mainly with mechanical problems, and that those which are particularly electrical in their bearing are minor in number. In fact, after the electrical engineer specifies a few general conditions as to conductivity and gives his attention particularly to insulators, the rest consists of matters which pertain to mechanical and economical problems.

Mr. Blackwell has pointed out the principal causes of the interruption of lines as they are now constructed. The new type of construction moreover apparently removes in a large measure all the principal causes of interruption to service in present lines; this is a very strong argument for the tower construction.

The discussion in the paper with regard to the characteristics of conductors and making comparison between copper, aluminum, and iron are of much interest, particularly the data upon copper cable. The difference between the elasticity of the wire and the cable, the latter being, as Mr. Blackwell expressed it, in the nature of a spiral spring, is noteworthy. One of the elements in this type of construction is the probable change in length of the conductor due to temperature variation. If the conductor could be made a spiral spring or if the twisting of the cable could even be carried to a greater extent than it is in the ordinary cable, then the conductor might be given a great elasticity and the limitations which are reached due to the variable sag of the cable might, in a measure, be eliminated.

Mr. Blackwell did not state specifically the pressure which is used on the line to which he refers. The inference is, however, that it is 60 000 volts.

N. J. NEALL: Has Mr. Blackwell any data to show the value of steel towers as lightning-arresters compared with standard lightning-arresters? and does he know of any case where steel towers were struck directly by lightning and what happened?

F. O. BLACKWELL: The speaker knows of a number of transmissions using pipe poles. In general it would appear that there is less trouble from lightning with an iron than with a wooden construction. Should lightning actually strike the line it would naturally go down the first pole. It would do no damage to a metal pole but would shatter a wooden one. With wooden poles there was always evidence left in the burning of or splinters from the pole, but with an iron pole you might have a stroke of lightning and never know it, except for a short circuit on the line, or unless an insulator were broken, which is rather improbable.

N. J. NEALL: Let us assume a case of a 60 000-volt transmission line in a mountainous country, such, for example, as in the far West. How would the cost of steel towers compare with the best present wood pole construction?

F. O. BLACKWELL: The comparative cost of steel towers and wooden poles can hardly be definitely stated, as it varies with the locality and the conditions. In this country, a wooden construction would almost invariably be cheaper as the tower system would be about equivalent to a cost of, say $10.00 per wooden pole. The steel tower in the tropics, where wood will not last any length of time, is essential; in this country, the speaker considers the use of a metal construction preferable on account of its more permanent character. The use of steel for long-distance transmission will probably supplant wood in order to get a more permanent and reliable construction. Where there is more than one circuit on a pole the necessary distance between conductors—to avoid the danger of short-circuiting—requires such a long cross-arm that it is essential to use two wooden poles in order properly to support the cross-arm. This, of course, doubles the cost of a wooden pole-line but makes practically no difference in the cost of a steel-tower construction.

A cable is preferable to a solid wire because it is more reliable and more elastic. The cable is flexible, which makes it less liable to damage during construction and from the swinging of the conductor in the wind. Should one strand of a cable break the whole conductor will not come down and the broken strand can be repaired at any convenient time. With a cable we can use a more brittle wire which has a much greater strength per square inch than would be possible safely to employ were a solid conductor used.

Regarding telephone circuits, it does not appear to the speaker that there is any disadvantage in the use of a metal structure; in fact, there is an advantage in that it is impossible

for high-pressure current to leak from the tower wires to the telephone circuit as it could on a wet wooden pole, which is a conductor of high resistance, whereas the tower is always grounded. It is most undesirable to do any work on a high-pressure circuit when it is alive. Wherever possible, multiple circuits should be employed so that one of them can be cut out for repairs without interrupting the tower service.

WM. HOOPES: A few words may be devoted to the aspect of this paper towards the comparison drawn between aluminum and copper for work of this character. By inspection of page 561 of the paper, it would appear that a sag of aluminum of 53 feet may be expected in a 100-ft. span.

Two and one-half years ago, the Pittsburg Reduction Company erected on a bluff 300 feet high, on the Allegheny River, in one of the most exposed situations in Western Pennsylvania, four 1000-ft. spans of No. 0000 aluminum wire, for the purpose of determining what might be expected from such a span.

Observations taken on these spans on June 17, with a temperature of 80° fahr., showed a sag of 22 feet. As the sun was shining at the time the observation was taken, the temperature of the wire should be taken as 105°, using the figure assumed in the paper as being correct; *i.e.*, that the wire would be 25° hotter than the air, due to the sunshine. The minimum temperature since the spans were erected was −14°, making a total range of temperature between the minimum and the time of observation of 119°. The paper assumes that a further rise of temperature of 56° may occur; if it does, the sag of the wire will be 27 feet. There is therefore considerable discrepancy between what actually has happened in such a span (which is about representative of what is likely to occur) and the 53-ft. sag which the paper says may be expected.

The reason for this discrepancy is the difference between the conditions which have actually occurred and the conditions which the paper contemplates as possible. The conditions contemplated by the paper are:

1. That the wind will blow with an actual velocity of 100 miles per hour.

2. That such a wind velocity will be coincident with minimum temperature.

3. That the direction of the wind will be at right angles to the line.

If any section 100 miles square were selected and a pole line built across it, by assembling what data is available from the U. S. Weather Bureau and applying the theory of probabilities, we would find that a combination of these conditions is not likely to occur oftener than about once in 20 000 years.

The Government reports give the velocities as actually indicated by the standard anemometer. These figures require a considerable change to convert them to true velocities. One hundred miles actual velocity would be reported as 135 miles

per hour. Such a velocity is almost unknown in the annals of the Weather Bureau. A search of the Bureau reports for six years shows for 28 widely scattered stations a maximum indicated velocity of 86 miles, or an actual velocity of 68 miles per hour. None of the maximum velocities have occurred coincidently with low temperatures and it does not seem within the range of probability that they will so occur. The maximum velocity occurring in Chicago last winter when the thermometer was below zero was 38 miles per hour indicated.

The only wind which actually seems likely to do harm to a line of this character is a tornado, and which it is impossible to erect any line to withstand, since the effects of tornadoes have been observed which must have been due to an actual velocity of 300 miles per hour, or a pressure of 360 pounds per square foot. Provision against this would involve a cost of construction absolutely prohibitory. Aside from the tornado the most severe condition a long span line is likely to be called upon to withstand, so far as wind strain is concerned, is a wind velocity of 40 miles per hour, occurring at from 20 to 30 degrees above the minimum temperature.

Although the conditions assumed in the paper seem unlikely to occur, it is worth while to consider what would take place with a line not designed to meet these conditions but to meet those which actually seem probable. Such a line using aluminum of the size referred to in the paper would be erected to have a sag, at minimum temperature, of 13.25 feet, and a tension of 11 000 pounds per square inch, the elastic limit being 14 000 pounds per square inch. If in that condition it were subjected to a 100 mile wind, at right angles, the effect would be to stretch the wire, not to break it, so that a sag of 42 feet would take place, which upon cessation of the wind would become 38 feet.

The effect upon the wire would be permanently to stretch it about four feet. It will withstand an elongation of 16 feet before rupture, and there really exists, therefore, a factor of safety of four, against breakage, even when the improbable conditions here chosen are used as the basis of calculation.

It is to be noted that in the case of spans of wire, the real factor of safety is not the ratio between the strength and the strain, which is the usual definition, but the ratio between the elongation at rupture and the possible elongation.

With regard to the strains due to sleet, there seems to be no limit to the amount of sleet which may gather on wire and it is very doubtful if the assumption of a depth of one inch for the deposit provides for the probabilities. If it is to be considered at all, a greater thickness should be considered as possible. However, the opinion of most practical transmission engineers, based on experience, seems to be, that sleet does not form on high-tension wires, and that its consideration does not therefore constitute an element of the problem.

With regard to the necessary strength of supports, and therefore their cost, the most severe requirement is most lightly touched on in the paper. This condition will be when, for any reason, all three conductors part in the same span, leaving the unbalanced strain to be taken care of by the supports, which supports must be strong enough to withstand this strain, as in the event of such an occurrence several miles of the line might go down, if they are not so constructed. If the supports are made strong enough to meet this condition, they will be amply strong enough to meet the wind strains calculated, since the side strains due to the wind are less than one-fifth the longitudinal strains produced by this condition. It also becomes apparent in this connection that, if a maximum strain per conductor of 5000 pounds for copper and 2500 pounds for aluminum is allowed, the towers will have to be twice as strong for copper as for aluminum. If, on the other hand, the strain per conductor is to be kept down to 2500 pounds, the maximum sag of the copper will be about the same as that of the aluminum, instead of about one-half as much, as shown in the paper. The expediency of allowing the amount of sag designated appears very doubtful, since, if the improbable conditions assumed do occur, the only effect will be, not to break the wires and interrupt service, but to introduce a sag, which can be removed at leisure. To allow the amount of sag calculated, if not necessary, forfeits considerable advantage, because if such a line were constructed on 75-ft. towers, for instance, and a sag of 50 feet allowed, the wires at the center of the span, being only 25 feet from the ground, could easily be short circuited by malicious persons. On the contrary, if a sag of 30 feet only be allowed, (which is all that is probably necessary), a clearance of 45 feet is obtained, and malicious interference becomes very difficult, and, therefore, improbable.

It would appear to be the best practice on a line of this sort, to erect the conductors so that they would reach a maximum tension at a minimum temperature of about 80% of their elastic limit, without considering the wind as a strain producer. If this is done, it will be only on very rare occasions that the wind or other causes will permanently stretch the wires and produce a greater sag than is contemplated, and this, when it does happen, will be on short stretches of the line only, making repairs a matter to be done at a convenient time and at very slight expense.

One result of following the method of calculation in the paper is that the sag to be allowed for every different size of wire would be different, although the wire is of the same material. This is because the wind pressure varies directly as the diameter of the wire, while the strength to resist the wind pressure varies as the square of the diameter. If the calculations on which the paper is based had been made for No. 1 copper, instead of No. 000 copper, the results would have been entirely

different and the maximum sags to be provided for very much greater.

F. O. BLACKWELL (by letter): Referring to Mr. Hoopes' comments, the writer affirms that it was not his intention to lay down any rules for the sag employed in long spans but to give the data and formulas which can be used in figuring upon them.

The maximum strain in the conductor and the wind pressure which should be assumed are matters of engineering judgment. A wind pressure of 40 lb. per sq. ft. is that commonly employed in making the calculations upon practically all engineering structures, and, therefore, the writer would not take any less pressure without further data on the subject. A long-distance transmission line may cover a great deal of territory and if there is any high wind it is most likely to be interrupted by it. The fact that an isolated span with much less sag has been up for two or three years does not necessarily prove anything. The probabilities are that at the particular point at which the experimental span was erected no high winds have been experienced.

It does not impress the writer as being good engineering to put up a long span and then let it take its own sag by stretching the wire as Mr. Hoopes suggests, any more than it would be advisable to do the same thing in a suspension bridge.

The writer does not agree with Mr. Hoopes regarding the strains to which towers are subjected lengthwise of the line. The ordinary tie-wire which attaches the conductor to the insulator will not bear any considerable strain. If a conductor breaks it always slips over the insulators for a considerable distance on both sides of the break and distributes the strain, due to the tension in the conductor, over a number of insulators and towers. As Mr. Hoopes states, the amount of sag to be allowed varies with different sizes of wires. Each transmission must therefore be calculated separately and no tables or curves can be given which will cover all conditions.

EUGENE CLARK: The speaker is particularly interested in the paper by Mr. Blackwell, because he argues for better mechanical strength in the pole line, which is generally conceded to be the weakest point in an electrical system. The speaker thinks it possible, however, that Mr. Blackwell might have left the impression that line construction with steel poles would be just as cheap as similar construction with wooden poles, and if this were true, he wishes to offer a correction to that impression. The speaker objects to the figure of $10.00 a pole which Mr. Blackwell has submitted as the equivalent in wood, of steel construction, The speaker knows that steel poles have long been in use in many steel plants of the country, not for the purpose of securing longer spans for light wires, but for the purpose of securing better mechanical construction for the exceedingly heavy lines necessitated by the large amounts of power carried at low pressures in such plants.

That the cost of such poles, which are quite heavy, varies from $60.00 to $120.00 each, erected, including cross-arms, concrete foundations, etc. One steel company has recently had occasion to cross a navigable river, and to do so found it necessary to put up very high steel towers. In this case, the total cost of each tower amounted to more than $1500.00.

The speaker believes thoroughly ,however, in the advisability of the superior mechanical construction made possible by the use of steel poles, calling attention to the fact that moving machinery, such as cranes and hoists, is commonly designed with factors of safety of from 5 to 8; whereas, the factor of safety on pole lines, as frequently constructed, scarcely amounts to 2 or 3 for ordinary service. The factor of safety should be at least as high on a pole line as on moving machinery.

PRESIDENT ARNOLD: The New York Central engineers also investigated pretty thoroughly the matter of steel poles. They began with steel poles that cost approximately $200 each; by dint of much effort they were finally estimated to cost about $80 each. The argument in favor of steel poles is strongest for the long-distance transmission lines running across country where the poles can be spread as far apart as will be justified by mechanical consideration. In cities the poles must be placed close together, necessitating the use of a larger number of steel poles per mile of line than would obtain in the country; this increases materially the cost of the line as obviously steel poles cost more than wooden ones. As Mr. Blackwell says, where the wooden poles are expensive, as in Mexico, the transportation of wooden poles is likely to make them cost as much or more than the steel towers. On the Guanajuato plant the cost was much less with five steel poles to the mile than it would have been with wooden poles spaced the ordinary distance apart. So the question is always one of the relative cost of wood versus steel *in position*. In the speaker's opinion there is no doubt about the desirability of steel poles; the question is rather one of getting sufficient poles to carry the line at a price that will justify their use.

The engineers of the New York Central road have decided upon overhead transmission for most of the line and for these two reasons: first, less first cost; secondly, the likelihood of less trouble with overhead lines than with underground cable—all this notwithstanding Mr. Carlton's statement. His statement is undoubtedly correct, but it seems that he refers to a specific case. The evidence in the New York Central case showed that they might expect less trouble with overhead transmission lines running across country than with an underground cable. For these reasons cable is being installed only in New York and its vicinity, where the use of cables is practically compulsory. A pressure of 11 000 volts will be used on this system. There will be six wires, two circuits, and the spans will be made as long as the conditions will admit. There

is quite a number of curves in the track which necessitates putting the poles closer together than in an ordinary construction. The bridge engineers of the company are figuring the relative cost of poles; the poles are approximately between 16 and 18 inches at the base and 45 ft. high.

In further explanation of why the engineers of the New York Central adopted the overhead plan it might be said that the possibility of trouble on the line was taken into consideration; for with overhead construction trouble can be located and remedied quickly and easily, much more so than would be the case with an underground cable. The objection to cable seems to be that when anything happens the trouble can be neither located nor repaired promptly.

EUGENE CLARK: It does not make so much difference about the angle-iron, if the rails are good in the first place, but the construction of the pole must be rather unusual. The common poles that the speaker referred to as costing $60 and $120, consist of four irons latticed together, on the other side with rounds to form the ladder. The speaker does not see how you can get that amount of steel in for $15, if it is steel.

W. D. BALL: The South Side Suburban Railway Company of Chicago has ordered a few poles on trial, and information regarding their cost and weight may be of interest. The poles in question were 30 ft. high, weighing 616 lb. each, and the price f.o.b. cars Chicago or vicinity was a little less than three cents a lb. The actual cost of the pole is considerably less than any other type on the market, as it weighs less for any given strength and the cost per lb. is a trifle less, as tubular poles were quoted from three to three and a half cents. The construction consists of three U-section steel uprights tied together with special malleable castings every two feet or 30 inches. The poles in question were six inches, at the top and thirteen inches at base.

RALPH D. MERSHON: There are two matters in connection with steel towers which have not been referred to; one of them is the amount of torsion that the steel tower shown by Mr. Blackwell can resist in case one or more of the conductors should break. The speaker knows of one instance where a latticed steel pole was erected, where no allowance was made for torsional stresses with the result that every time a wire broke there was considerable trouble.

Another matter in connection with steel supporting structures with long spans is the question of repairs. A span of say 150 feet is easier to repair than a much longer span; this means that in case of a break in the line the power service will be interrupted for only a comparatively short time. In comparing this type of construction with other types the first cost alone should not be considered; we should consider everything which goes to make up the total cost; first cost, maintenance, etc.

It seems to the speaker that there is one point in which the steel tower construction falls short of what is claimed for it. Although it is true that the conductor will, for the greater part of its length, be higher than an ordinary pole-line, still with the construction described by Mr. Blackwell, the conductor is only about 25 feet from the ground, making it easy to short circuit the line at this point with a bale wire as in the case of a shorter span and lower pole.

N. J. NEALL: The following facts should be borne in mind with respect to the development of steel towers; some of the more recent wooden pole constructions are very stable; a number of lines have been built with a great deal of attention to the mechanical features, heavier poles and greater strength throughout, and the maintenance of an almost continuous line service for a year or more would indicate that the wooden pole line has been developed very materially. When you have such a construction near the base of supplies, it may require more than the arguments brought out to-day to substitute steel towers for wood. In the case cited by Mr. Blackwell where wood is as difficult to obtain as steel, it is perhaps more economical to make use of the steel tower. In cities and their outlying districts still other conditions enter, and it might be easily advisable that the tower construction, even though more expensive, should be employed.

In addition to the emphasis given the advantages pointed out by Mr. Blackwell for metal towers, it does not appear from the discussion that the cost of such a tower construction is, broadly speaking, prohibitive. The advantages of the metal tower as a lightning-arrester seem to be unduly emphasized. The metal tower might be considered as having approximately the same discharge value as an overhead grounded wire on a wooden pole-line, and it is obvious that in view of the fractional value of such protection we are in no degree relieved from having protective apparatus in the stations. The discharge value of the metal tower seems only incidental to its other advantages.

CHAS. F. SCOTT: We are getting on the wrong line of discussion with reference to Mr. Blackwell's paper. While the cost, the relative cost, of the two different types of construction is an important thing to consider, it is not the only thing. Mr. Blackwell does not begin his paper with the consideration of cost or to find something that is cheaper. He begins it: "Unfortunately interruptions of the power service occur not infrequently and when they do happen they so inconvenience the public as to be most conspicuous."

It is a better kind of service, a different order of construction that he is seeking for; he finds out how that construction will overcome present difficulties. Sometimes cost is important; sometimes it is relatively unimportant. A few years ago an engineer who was making a preliminary layout of a trans-

mission plant asked the speaker what he thought of the engineer's transmission system; it was 20 miles in length, and he proposed to use one pole line and two circuits of 30 000 volts. The engineer was told that his pressure was very high and he was putting a good deal on a one-pole line, and as he wanted reliability he would better consider lower pressure and two separate pole lines. The cost of the line complete, conductors, poles, insulators—the whole cost as the speaker remembers—was something like four per cent. of the total investment. Here, then, was the element in the system upon which the continuity and reliability of service depended—the most vital element in the whole system, and he had gotten it down to four per cent. of the whole investment. By increasing that element, say doubling its cost, and running two pole lines say of 20 000 volts each, he would increase his total cost only a few per cent. and he would increase his coefficient of reliability by a very much greater per cent. So in the general question now under discussion, we have to consider, first the general engineering condition, which would be the best plan and would give the most reliable service; and then determine as to the cost. This paper should be considered on its general engineering merits, and it seems to the speaker that Mr. Blackwell's points are pretty well taken.

Another thing: we have been comparing a new type of construction with certain lines and poles now used. We are coming into a different order of conditions in power transmission—the circuits are of greater output, higher pressure, and greater importance. Where there are many circuits, with large and heavy wire, where continuity of service is of the utmost importance, where the cost of the line could often be considerably increased in order to increase the coefficient of reliability, then we must consider the problem from an entirely new standpoint. In these respects the lines laid down in this paper are very promising.

F. A. C. PERRINE: While agreeing entirely with Mr. Blackwell and Mr. Scott in the statement that reliability is more important than cost in long distance transmission, the speaker believes that a number of points raised by Mr. Blackwell require consideration.

As regards the limit of transmission with any particular size wire it may be noted that up to 40 000 volts no wire of sufficient strength to be employed in a transmission line is small enough to allow discharge through the air, consequently allowing the rule that the practice in transmission pressure is to employ about 1000 volts per mile. The question of limiting size of wire is not of importance until the distance exceeds 30 or 35 miles. For longer lines where the pressure is between 40 000 and 60 000 volts no wire smaller than $\frac{3}{8}$ in. in diameter may be used; since Mr. Scott has already shown in the paper referred to that at such pressures a wire $\frac{1}{4}$ in. in diameter will discharge

a large amount of energy. This necessity for the use of a large wire on long lines is one of the advantages in the use of aluminum, an advantage not noticed by Mr. Blackwell in his paper. This is particularly an advantage of aluminum, since where small amounts of energy must be transmitted over a wire of a definite size the loss is not important, and the aluminum wire is very much cheaper than the copper wire of the same size. These large wires are invariably made stranded, as in this form they are more reliable than any solid wire of the same area, on account of the fact that the smaller wire has a high tensile strength and by reason of the fact that the weak places are distributed along its length. The writer believes that Mr. Blackwell is in error when he states on page 557 strands are made of unjointed wire. The practice amongst manufacturers being to joint reel after reel in their machine, cutting off the completed strand in the required lengths without reference to the lengths of wire on the spools of the machine which are jointed as required. Experience has shown that the large strand which must be employed in very long lines gives no trouble in breaking.

The speaker knows of very few instances where strands of over 0.5 inch in diameter have been burned off; the few cases occurring have been due to a solid short circuit where the station fuses did not operate, but it is generally the case that the station fuses operate before the line wire is fused.

Attention must be called to an additional advantage of tower construction, that it permits the use of large cross-arms supporting the very heavy insulators which must be used in the higher pressure construction. Insulators at present weighing from 30 to 50 pounds are common, and with electrical pressures increasing the present tendency is toward larger insulators weighing as much as 100 pounds. Some insulators now in use cannot be installed on a wooden cross-arm less than 6 by 6 inches, which arm cannot be securely supported on a wooden pole with a 9-inch top. In consequence the steel tower, whether the cross-arm be of steel or wood, is probably capable of furnishing the more reliable type of construction, since in long-distance transmission lines we must decrease the number of insulators by lengthening the spans and correspondingly increase the size of the insulator. This can only be accomplished by the use of the steel tower.

The value of the steel tower as a lightning-arrester the speaker considers very important. He believes that to-day the advantage from the use of a grounded wire for protecting the long-distance transmission lines is unquestioned, though there is decided difference of opinion concerning its permanence; but with the steel-tower construction a sufficient number of grounded points are brought close to the wire without the use of an extra wire. On one transmission line with which the speaker is familiar there is a section 37 miles in length where the average

span is 300 feet; this section is one-third of the line and extends over a series of low hills. Such lines can undoubtedly be made more permanent if steel towers are used in place of the wooden poles. While not an advocate of the steel-tower construction for short lines and low pressures, the speaker strongly believes in the steel-tower construction for long lines and high pressures; first, because of the increased value of insulation by reason of a lesser number of insulators; secondly, because of the lightning protection afforded; thirdly, because of the permanence of the towers themselves, and because of the fact that they allow the use of a cross-arm which will support a larger insulator and a larger wire.

Finally the speaker would call attention to what he believes to be an error in Mr. Blackwell's Introduction, pages 560 to 562, where he makes use of the standard coefficient of linear expansion in calculating the temperature changes. This is not correct unless the modulus of elasticity is introduced into the equation, which then becomes too complicated for solution. If a fictive coefficient of expansion based on experiments at different temperatures with actual spans, then the form can be considered correct.

The equivalent cross-section of a solid wire will have a lower tensile strength than a strand, because the wires of a strand have been subjected to an increased amount of working and are consequently harder. Furthermore the weak places in a strand are distributed. In consequence the strength of a strand is proportionally more than one would expect from the decreased size of the wire.

RALPH D. MERSHON: Does Dr. Perrine mean that the ultimate strength of the cable will be greater than the sum of the ultimate strengths of the individual wires?

F. A. C. PERRINE: Yes; so far as the speaker knows, with copper, with soft strands. That is absoultely untrue with steel, with metal that will not crush.

EUGENE CLARK: The speaker calls attention, as being of interest in this connection, to the fact that hoisting ropes used on cranes built to handle molten metal have been made with cores of soft iron wire, or of asbestos, it being necessary to use a fireproof material. In practice, it is found that the strain on the ropes acts to extend the helices formed by the outside strands of the rope. In the case of asbestos-cored rope, the core would break at various points throughout the length of the rope and separate, so that sometimes 18-in. or 24-in. space intervenes between the two broken ends of the core. The result would be to allow the rope to flatten at that point. In the case of the soft iron-cored ropes, the iron core was cut out of the rope at each end. When the rope stretched, the iron core was stretched enough to pull through and leave the open space at each end of the rope, where it caused no damage. In view of these facts, the speaker feels convinced that a central straight strand for a

transmission cable would certainly receive more strain than the outside strands.

RALPH D. MERSHON: It seems to the speaker that Dr. Perrine overrates the question of lightning protection from steel towers. The speaker does not see how a steel tower can be the equivalent of a ground-wire, nor how a steel tower can ward off electrostatic induction. The tower might take a lightning stroke, but it does not seem that it could be of any protection from effects due to electrostatic induction or from lightning strokes which might get into the line-wire. In the latter case the charge will probably jump to a pole, but in doing so will probably shatter an insulator. The speaker does not recall any case where a wooden pole has been shattered by lightning where the insulators on that pole have not, one or more of them, been shattered. It isn't a case of simply flashing-over the insulator, nor is it a case of flashing-round or yet a case of puncture. In most cases the insulators go all to pieces; the speaker knows of one case where a pole on a high-pressure line was struck by lightning and an insulator smashed to pieces; the French Canadian patrolman who reported upon this occurrence said in his report: " I found pieces of her over in the field; if she had been hit by a stone she would not have gone so far."

Dr. Perrine and Mr. Scott have both said the cost is not the important question. This the speaker cannot agree with, for he believes that cost is the only question; not necessarily first cost but the total cost, including interest, depreciation, etc. Into this cost must enter and be considered the question of reliability, a question which cannot easily be evaluated in dollars and cents. Its weight and valuation must enter into the calculation through the medium of the engineer's judgment. It is easy to imagine a situation where, with a type of construction subject to mishaps resulting in interruption to service, a plant might be a commercial success in spite of occasional interruptions, but where the cost of absolutely reliable service would swamp the enterprise; on the other hand, there are situations where anything less than the very best and most reliable construction would swamp it. It is all a question of cost, and of cost proportional to the conditions to be met.

W. B. JACKSON: The speaker fully agrees with the statements that the iron tower would seem to be excellent as a lightning protection.

The speaker does not agree with Mr. Mershon that the lightning in jumping around the insulators as a rule breaks them. For instance, in a 20 000-volt transmission line, with which the speaker is familiar, the lightning has struck the line a number of times and smashed one or more poles at or near the point of striking and has then run along the line each way jumping around the insulators for several poles consecutively, slightly splintering the poles. It was seldom the case that the insulators were broken in the discharge of the current over

them. It was usually possible to replace the broken poles by setting a new pole immediately alongside of the broken one and transferring the cross-arm and the pole-top insulator without further repairs. In the case of the steel towers there would apparently be little tendency toward the destruction of the tower, and should the lightning strike the line it would have a tendency to run along the line and relieve itself over the insulators at the adjacent towers.

Referring again to the line mentioned before; it was not infrequently struck at points between the lightning-arrester stations, and sometimes struck hard without any indication whatsoever of the discharge getting as far as the lightning-arrester stations, though indications of its leaving the line over the insulators was amply abundant.

As already indicated it is entirely possible that the lightning might strike between the supports in the case of iron towers and run either way along the line, dissipating itself through induction and by discharge to the towers. Of course the exact action under these conditions cannot be predicted with any certainty, especially as with the steel-tower construction we generally associate the higher pressures such as 60 000 to 80 000 volts, and so must solve the problem according to our best judgment considering that we have no operating data to work upon—but we must always remember that lightning works according to ways other than our own.

There is another feature in connection with the tower construction that has been brought out a very little this morning, that would seem to warrant further consideration. It has not been uncommon on 20 000-volt transmission lines and even 30 000- and 35 000-volt lines that a wire of the transmission circuit has dropped on to the cross-arm carrying wires and no one has been the wiser for the fact until the line inspector discovered it. In the case of the steel tower, the dropping of one of the wires upon the support might be indeed serious, owing to the fact that the wire would probably be burned off at the point of contact, with disastrous results; thus the problem of the mechanical strength of the insulator and the attachment of the cable thereto is of paramount importance. As Dr. Perrine has pointed out, there is extremely little chance of a properly constructed cable breaking except under abnormal conditions, therefore, the absolute certainty of support of the cable is of the greatest importance, for if there is danger of the insulator breaking, or the attachment of the wire to the insulator giving way, the possibility of the wire being burned off would be considerable. With the long spans and heavy cables that would usually be contemplated in connection with steel towers, the breaking of the wire might be a catastrophe of real magnitude.

Except in extraordinary situations, the speaker's feeling is that a well-constructed pole line using wooden poles and wooden

cross-arms must continue to be the most satisfactory construction for transmission lines, so far as general practice is concerned in this country.

A conversation which the speaker had with Mr. Blathy of Ganz & Company at Budapest may be interesting: he remarked that it would be unwise to attempt to employ 35 000 or 40 000 volts in accordance with the usual European practice in transmission work considering the status of the insulator at that time, and asked: "What do you think would be the best to do under the circumstances?" My reply was, to use the usual iron poles but attach wooden cross-arms to them. He replied that they would not permit such unsightly construction as this would necessitate, though he felt that the wooden cross-arm was a material advantage.

H. B. ALVERSON: In regard to lightning on lines of 11 000 volts and 22 000 volts, our experience has been that where it struck, the insulators would be shattered. Either way from this point the insulator would usually be punctured, while slightly farther away no damage would be done. At the time when the lightning struck the line, the circuit would be short circuited, undoubtedly at the point where it struck. In the case of a steel tower line this would probably cause the shutting off of current before enough time has elapsed to burn off the cables.

PETER JUNKERSFELD: Mr. Mershon's statement that cost of the transmission line is everything, cannot, it seems, be generally accepted without some qualification. If the owners or managers of the line are interested simply in receiving and delivering power without much restriction or responsibility, the statement might hold. In that case, however, it is only a temporary or perhaps expedient commercial organization, because for ultimate and permanent success we must consider everything all along the various steps from prime mover to the individual consumer.

"Reliability of service" is a term that must be used relatively and usually should be the first consideration, the second being the securing of such reliability for the lowest permanent annual expenditure. This reliability of service is always extremely important. In large cities even with the principal high-pressure transmission underground, this represents a comparatively small part of the total investment in the central station system, and it would seem unwise even for some considerable difference in total cost of high-pressure transmission to take chances with the particular part of the central station system which represents perhaps the greatest responsibility and least annual expenditure per unit of output.

Similarly in the New York Central's present undertaking, the cost of high pressure transmission must be small compared to the total when we consider car equipment, track construction, power and substations, and so on. For reliability let us

compare a duplicate overhead line, six wires on the same set of poles, with a duplicate underground line both in same group of conduit, assuming best construction in each case. In both cases the conductors are heavy enough so that loss of one line will not interrupt the service. Assume now that probability of breakdown in insulation of conductors is nearly equal in the overhead and underground construction, the probability of external injury of all possible kinds is very much greater with the overhead lines. In event of serious short circuit on one line, the probability of both lines being disabled, resulting in a total shut-down of lines, would seem greater with overhead construction, as the two overhead lines on same pole cannot be isolated, while the underground lines can. Experience and observation would indicate that ordinarily with transmission at 11 000 volts, good underground construction would be much more reliable.

In the question of overhead and underground transmission for the particular case of the New York Central, it is probable that there were a number of unusual conditions not generally known. The estimated cost of underground being seven or eight times that of overhead construction, indicates at least one very unusual condition. The annual expenditures, however, on account of transmission lines operation and maintenance, would not be in the same proportion.

PRESIDENT ARNOLD: Mr. Benezett Williams has requested that the speaker ask this question:

"What would be the effect on the permissible voltage by the protection of the insulators and cross-arms from rain, snow and sleet; that is, how much above 60 000 volts could the pressure be carried?"

The general question is, what kind of protection should the insulators and cross-arms have from rain, snow, and sleet?

F. A. C. PERRINE: The speaker wishes to present a proposed construction for discussion; this construction is designed for a 350-mile, 80 000-volt line. On investigating it was found that a 14 by 14 insulator was small enough for 60 000 volts, but it was a question whether any reasonable-sized insulators for use out of doors could be made for 80 000 volts. Furthermore, it was found that with a duplicate three-phase line, if one line was out of service for repair the regulation of a single line would be so bad that the service could not be maintained. In other words, in trying to get along with half the copper the regulation would be too bad to give any kind of service. Consequently a system was proposed involving the erection on a tower of a house about ten feet square with four wires on insulators in separate compartments each being five feet square and ten feet long, the idea being to put the insulators in an enclosed house having four wires all told; three wires being in service at any one time, the other wire being out of service for cleaning insulators and for repair. In that way enough metal

could be concentrated on three wires to ensure regulation. In addition the tower was to be provided every 10 miles with a switching station, so the service of any one wire could be switched on any of the four.

In regard to the covering of insulators, the Kontenric Company in British Columbia has built a line with a pent-house over each insulator but from this they have not derived any very great advantage, for while the pent-house protects the insulators against rain or snow it does not protect them against dust and fog; the combination of dust and fog makes mud, producing the worst possible conditions. In estimating this line, 18 000 volts were figured on.

H. C. WIRT: Will President Arnold say whether the New York Central lines are to be operated with the Y connection grounded? There seems to be a difference of opinion in reference to the advantage of operating in this manner.

PRESIDENT ARNOLD: No; it is not intended to run it under abnormal conditions; provision is made in the power-houses and sub-stations for grounding whenever the engineers see fit to use the ground wire.

N. J. NEALL: Dr. Perrine has brought out very justly the advantages shown by Mr. Blckwell's paper, and moreover the discussion has brought out the fact of a cost that is prohibitive; but it seems that in addition to what has been said as to the advantages electrically, it is not out of the question from a financial standpoint. One matter seems to have been given undue emphasis; that is, the lightning protection. Last year at Niagara we were discussing the advantage the barbed-wire or the ground-wire had over the transmission, that it was a good thing to take off some of the static discharges. You must remember that when you have a climatic disturbance you have an electrostatic disturbance, and an electromagnetic disturbance. The steel tower, and for that matter the barbed-wire protector, does not in any degree relieve us from having protection in the stations. And the electrostatic can be taken to some extent by the entire line, but only incidentally. The best protective apparatus to-day provides for the discharge of this disturbance as well as the electromagnetic. We cannot consider the steel tower as having anything more than an incidental advantage, but they are better than wooden poles because they will absorb from the atmosphere some of the static disturbance.

F. O. BLACKWELL: There is another thing in connection with steel-tower construction. The towers can generally be located on high ground, so that the maximum sag will occur over the low ground between towers. A tower would naturally be located at the highest point—on every hill which is passed over—these are the points which would naturally be struck by lightning, and the towers, if especially provided with points projecting above the line, will take a lightning charge without

affecting the system. Wherever there is a sudden change in altitude, or other conditions which cause lightning phenomena at certain points, there should be lightning-arresters connected to the circuits which will discharge them to ground.

N. J. NEALL: In consideration of the relatively great distance between cloud and line, the addition of lightning-rods to metal towers would probably not be as effective as Mr. Blackwell suggests, and hence for any direct strokes the metal towers should be able to attract and discharge these disturbances as well as if equipped with lightning-rods.

H. C. WIRT: Reports received from a few plants where ground-wires are used indicate that such wires prevent the shattering of the wooden poles and they also assist to protect the apparatus at stations and sub-stations. If the interruptions due to shattering of poles are frequent, it may be necessary to use ground-wires.

N. J. NEALL: Is the case referred to by Mr. Wirt regarded by him as general or special, because there have been plants where transmission lines have had their poles shattered and the continuity of service not disturbed. Any questions regarding overhead grounded wires are meant solely to bring out their value, not to disparage their use. If lightning has shattered poles and disturbed the service then any protection of the pole to eliminate this is indeed valuable. It seems too early to decide the worth of overhead grounded wires, and we must certainly wait until those who have had the courage to install this system and investigate its behavior report their observations; and even then to be of permanent value these observations must cover a wide geographical area and have lasted for more than one lightning season. So far these observations have been special. If we should take up the metal tower, then overhead grounded wires would probably not be used.

S. B. STORER: One of the speakers said in referring to the use of barbed-wire that he frequently obtained an extra high pressure between any two transmission lines. Now if a barbed-wire is added to the transmission line it seems to the speaker that the trouble is increased about one-third, because the same pressure might obtain between the grounded wire or between the barbed wire and the transmission wires that would obtain between any of the transmission wires.

H. C. WIRT:—Theory or laboratory tests should not be relied upon wholly in the design of lightning-arresters. We will have to work with the lines themselves and make extensive trials on any protective device that may be proposed. Recent examination of transformers that have burned out has shown that a very high pressure has existed from line to line. Attention is called to a photograph of a connection board printed in the speaker's paper. The tension necessary to make an arc go across the terminals was 42 000 volts, and the working

pressure was 2000 volts. Too much attention has been given in the design of lightning-arresters to provide an easy path to ground and too little to prevent a rise of pressure between line and line.

In low-pressure work we started with transformers using insulation between primary and secondary that would withstand two or three times the working pressure. We now have to insulate our transformers to withstand five times the working pressure of 2000 volts. With these modern transformers we find that the burn-outs due to lightning effects are from line to line and rarely from line to ground. With high-pressure transmission lines it would seem to be necessary to provide a path from line to line as well as from line to ground so as to prevent the lightning current making its own path through expensive apparatus.

In many cases reactive coils were used for protection. It is possible to have an electromagnetic effect in the line wires; that is, upon a heavy stroke of lightning passing to ground high-pressure currents are created in the transmission system.

R. F. HAYWARD (*by letter*): Since the commencement of transmission work in Utah the writer has maintained the opinion that structural strength and stability are the first requisites for transmission lines. Every year's experience has strengthened this opinion. There are now 500 miles of transmission pole-line in Utah, and experience has abundantly proved that the line which is mechanically strongest gives the best service.

Glass insulators are not mechanically strong enough, nor will they stand the continued stress of heat and cold. Wooden pins should not form part of a strong line. Iron pins have been used on all the corners of the Pioneer line between Ogden and Salt Lake, and there has been no failure on their account in seven years. Porcelain insulators have stood the test of strength thoroughly well. Where properly designed and made, they do not check or break except when shot, and then they only chip instead of flying to pieces like glass. In only two or three instances have short circuits been caused in the Ogden-Salt Lake line by insulators broken by a rifle shot, out of thousands which have been chipped by bullets.

On a transmission line, the failure of one pole or one insulator may cause an interruption of service and therefore the factor of safety should be very large. A line designed for 50 000 volts can be depended upon for 30 000 volts. If a transmission line cannot stand the cost of an expensive porcelain insulator there can be no profit in building it. There is little excuse for interference from trees, but it is more difficult than might be supposed to get rid of trees in settled districts. In eight years' service on the Ogden line the greatest amount of trouble has been caused by burning of poles from brush fires. Careful patrolling has kept the interruptions from this cause down to a very small amount, but on one occasion 15 poles

were burnt off in a sage-brush fire. In a few cases poles have been splintered and insulators shattered by direct lightning strokes. Except in these instances no breakdown of the line itself can be directly traced to lightning.

There have been many interruptions caused by wires or sticks thrown over the lines; a few by birds, and one by a wild-cat. Once only has a pole been blown down, while once the whole superstructure of a box car was blown from a train into the wires.

In the inter-mountain region wooden poles have a life of not more than ten years; many last only five years. It has been found that salt is the best preservative for the butts of poles, but if the butt is made to last ten years the upper part of a cedar pole will check and become so brittle that its useful life is gone in that time.

The writer in 1903 constructed a pole-line for the Utah Sugar Co. from their power-house on the Bear River to the Utah Light and Railway Company's power-house at Ogden, a distance of 45 miles. The line was designed for 40 000 volts, and is operated at 28 000. It is located at the base of the Wasatch range, just above cultivated ground, but within a few hundred yards of a good county road. The location was costly as regards pole construction, but was necessary in order to avoid trees. The line consists of 40-foot cedar poles with cross-arms. The wires are spaced on a six-foot triangle. The upper cross-arm is short and the insulator is placed on alternate sides of consecutive poles. This arrangement avoids the bad practice of placing a pin on the top of a pole. The lower cross-arm is heavily braced and the cross-arms are strengthened and prevented from splitting by $\frac{1}{8}$-in. steel plates held together by carriage bolts. Poles are spaced 44 to the mile. The line wire is No. 0, soft-drawn, solid copper. The insulators are three-part Locke brown porcelain. The upper part is 11-in. diameter, and was tested to 40 000 volts. The middle part was tested to 30 000 volts, and the lower to 50 000 volts. The pin is of cast iron with a collar $3\frac{1}{2}$-in. diameter and a $\frac{5}{8}$-in. steel bolt cast into the shank. It is cemented into the insulator with neat Portland cement. The pins and insulators complete weigh 20 lb. each and cost nearly $2.00 in place on the pole. They are heavy and expensive, but they are strong and make a splendid insulator for a heavy line.

In stringing wires half a mile of wire was stretched at a time, and the writer has repeatedly seen a single insulator stand the whole strain without any trouble. There are three long spans on this line, two of 250 feet and one of 450 feet. Solid No. 0 was used for these spans, and 15 feet sag allowed. The wires were supported by three insulators at each end, set in a special iron fixture. The whole strain of the span is taken by these insulators. All corner strains are taken by single insulators and they are strong enough to stand them. The

whole line was built for mechanical strength and so far it has given no trouble. Some 30 or 40 of these insulators have been in use through the past winter on outdoor 40 000-volt air-switches and have shown no sign of failure. The insulators are not expensive to repair, as the upper part when broken can be cracked off and a new part cemented in its place; the pin and the rest of the insulator are used over again.

This pole-line cost $2000 per mile, and has probably as much steel and iron in its construction as can be used on any wooden line. The next important line in Utah will undoubtedly be entirely steel supported, for a careful comparison of costs shows that the Bear River line, just described, could have been built just as cheaply with steel towers as with poles.

The writer believes that a single line of steel towers set 500 feet apart carrying two circuits of copper wire, spaced on six-foot triangles, will be much cheaper, both in first cost and maintenance, and freer from interruption and safer for repair work than two separate wooden pole lines.

It may be argued that if a wire from any cause drops on the structure it will make a dead short circuit. It will, but the wire will be burnt off in an instant and in a properly laid out and operated plant the trouble will be located and the section isolated without delay.

It would be interesting to get figures on the cost of erection of the steel towers, assuming labor at $1.50 per day, teams at $3.50 per day, and average length of haul four miles. The writer is not in favor of using aluminum cable. It is cheaper and lighter than copper, but it lacks the strength and may be worth very much less per pound in a few years, whereas copper is not liable to depreciate much in value.

A. S. HATCH (*by letter*): On page 512 it is assumed that the steel towers act as lightning-arresters. The writer cannot agree with the statement unless the tower is grounded in permanently moist earth. In testing the street lighting circuits for grounds or opens, it is found that the towers are not generally grounded in dry weather, being grounded but a few days after a storm. As a storm usually follows dry weather, at least before the rain has had time to penetrate any distance into the ground, the towers may be fairly well insulated by the dry earth. There have been several instances where lightning has struck a tower and, following a guy-wire to the wooden stub, has splintered it in passing to earth rather than follow the tower. In one case, lightning struck a tower and puncturing the lamp insulator discharged through the circuit which was grounded in the station. This experience, together with the statement made during discussion that the steel towers were usually located on high points of ground, emphasize the importance of grounding the towers thoroughly.

BLANK
PAGE

A paper presented at the 188th Meeting of the American Institute of Electrical Engineers, Chicago, June 21-22, 1904.

Copyright 1904, by A. I. E. E.

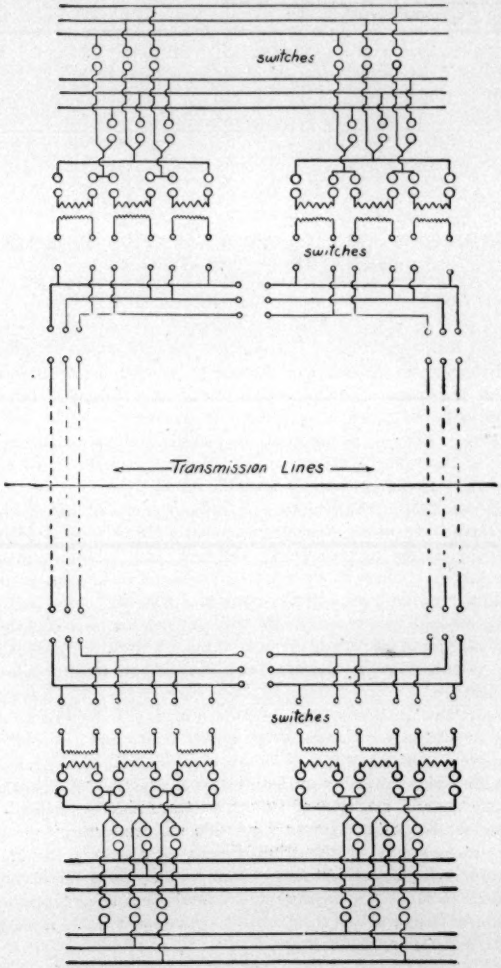
CONDITIONS FOR CONTINUOUS SERVICE OVER LINES OPERATED IN PARALLEL.

BY M. H. GERRY, JR.

In order to maintain a continuous service, nearly all of the more important transmission systems have installed two or more pole lines, each carrying one or more circuits. As a rule the circuits are operated in parallel but are so arranged that at least one of them may be entirely disconnected without interrupting the delivery of energy.

Two sets of conditions are met with in practice: first, normal operating conditions; secondly, accidental conditions. It is possible by design to provide for the first, and, in the main, for the second. The normal operating conditions include inspection, repairs, and additions to the circuits. But little work can be done on high-pressure circuits while in service, and it follows that adequate switching devices must be provided such that any circuit may be disconnected without an interruption of the service.

Both the air-break type of switch and the oil-switch are now available for pressures to 60 000 volts, and may be installed in various ways to obtain the desired results. They may be operated either automatically or manually. There are in use several systems of switching transmission circuits in parallel. Some arrangements provide for connecting only the low-pressure side of the transformers; others only the high-pressure side, and still others provide for the connecting of both the high- and the low-pressure sides in multiple. An arrangement of connections for two transmission circuits in parallel is shown in the accompanying diagram.


switches
switches
Transmission Lines
switches

This system may be elaborated by adding group-switches on one or both sides of the transformers. If more than two circuits, or more than two banks of transformers be employed, various devices are resorted to for providing the required flexibility. Practice in this last connection has taken the direction of sectionalized bus-bars, with some form of group switching. In addition to the switching devices at either end, it is desirable on long lines to install sectionalizing and paralleling switches so arranged that a section of a transmission circuit may be entirely isolated and the remainder continue in parallel with the other circuits. The switches for this purpose are usually mounted on the poles and are operated manually. It is probable that the practice of sectionalizing long transmission lines will be extended in future and that improved switching apparatus will be employed for this purpose.

In addition to normal operation, the accidental conditions which may arise and affect the continuity of the service should be anticipated and provided for. These conditions, whatever may be their primary cause, usually result in an open circuit, a short circuit, or a grounding of the conductors. Whenever one of these occurs it is essential that the entire circuit, or at least the defective section, be immediately isolated from the other circuits of the system. This may be accomplished either by automatic devices or by the attendants. The automatic methods, on account of the time-element involved, are undoubtedly superior, but the apparatus should be of thoroughly reliable construction and should be tested frequently if the best results are to be obtained. The best practice calls for circuit switches controlled automatically by means of time-limit overload relays at the generating end, and similar switches controlled by time-limit reverse-current relays at the receiving end. These devices properly installed will effectually isolate a transmission circuit in case of trouble, but other conditions must also be considered if the service is to be uninterrupted. Whenever a parallel circuit is disconnected it disturbs the entire system and especially affects the electrical pressure. A long transmission circuit represents a considerable capacity, inductance, and resistance, and when this is removed or placed in parallel to other circuits, it becomes necessary to readjust the pressure. This is usually done by the attendants at the generating station but a reliable automatic device would be of value for this purpose if designed to meet all the requirements of transmission service.

A considerable change in pressure at the receiving end of the line may result in an interruption if induction motors or synchronous apparatus be operated by the current. The greater the number of circuits in parallel, the smaller the amount of disturbance produced by removing a single circuit. Many of the better high-pressure transmissions depend, however, upon two lines of one circuit each, and in case of accidental difficulty with one of the circuits the entire load is carried temporarily on the other line. By a proper design this may be successfully accomplished, and even in the case where one of the circuits is suddenly isolated by automatic devices the variation of pressure may be kept within such limits that there will be no interference with the service.

The reliability of high-pressure and long-distance transmission has been thoroughly demonstrated, and it has been shown by actual results that a continuous service can be maintained for indefinite periods by the use of multiple lines and proper appliances.

Discussion on "Conditions for Continuous Service over Lines Operated in Parallel."

Ralph D. Mershon: There is one point which the speaker would like to have taken up, because of its bearing upon a previous discussion at Niagara Falls. The speaker refers to reverse-relay devices; they are interesting things to talk about, but does anyone know of a reverse-relay device that will work under all conditions?

P. H. Thomas (by letter): Absolutely continuous service may be realized in theory and ultimately will undoubtedly be closely approached in practice. At the present time, however, no such perfect devices are available.

The usual arrangement of overload circuit-breakers at the generator end of two transmission lines in parallel and reverse-current relay circuit-breakers at the other ends does not operate properly in all cases when there are generators at both ends of the line. A theoretically satisfactory arrangement can be constructed, however, which will open the right line at both ends in all cases of short circuits by operating at all points at which the lines are paralleled, the relays controlling the circuit-breakers jointly from current transformers connected in the two lines. These currents must be so directed that during an equal division of load between the lines (or division in any desired proportion if so desired) the influence of one line shall just neutralize the influence of the other line. When with this arrangement current is reversed in one of the transmission lines, the influence of two lines is in the same direction in the relay and can be made to open the defective line.

Another method appears to the writer to have a number of advantages. In endeavoring to maintain continuous service with apparatus now available, the system having duplicate parts all through may be operated as two systems entirely independent electrically, each so arranged as to carry approximately one-half load. Each of these systems should of course extend into all important sub-stations. In case of trouble to one line causing a drop of pressure, half of the load of the system will be dropped. Immediately this should be thrown to the other system, which must of course be able to carry the double load for a short time. If the attendants are properly instructed this may be done without special orders from headquarters, thus avoiding a very important loss of time. All parts of the dead system which are uninjured may then be immediately paralleled with the live system, enabling it to carry the full load easily.

BLANK
PAGE

A paper presented at the 188th Meeting of the American Institute of Electrical Engineers, Chicago, June 21-22, 1904.

Copyright 1904, by A. I. E. E.

THE USE OF GROUND-SHIELDS IN TRANSFORMERS.

BY J. S. PECK.

In any transformer there is a possibility that the high-pressure winding may become metallically connected to the low-pressure winding through failure of the insulation between these windings, so that if the low-pressure winding is not connected to ground it may be raised to a high potential above the earth. Under these conditions a person coming in contact with the low-pressure circuit may receive a dangerous shock, while the apparatus connected to this circuit is subjected to undue strains. If, however, the low-pressure winding is connected to ground, the maximum difference of potential which can exist between any part of it and ground is that which is established between the grounded point and that portion of the winding farthest removed, electrically, from the ground.

The ground-shield is a metallic sheet so placed between the high- and low-pressure windings of a transformer that the high pressure cannot break through to the low pressure without first going to ground. The ground-shield should be made preferably of copper, of a thickness of approximately 1/32 in., though it may be of any conducting material, and of practically any thickness desired. A convenient arrangement is to connect the ground-shield to the core of the transformer, which is grounded directly, or through the case. It is obvious that since the ground-shield surrounds the magnetic circuit it must not form a complete turn, and for this reason it is cut through in one place and the joint insulated.

While upon first thought the use of a ground-shield would appear to eliminate entirely the possibility of an abnormal pressure existing between low-pressure winding and ground,

there are, nevertheless, ways in which it may fail in accomplishing its purpose, and there are numerous practical difficulties in its use, particularly in large high-pressure transformers.

Some of the objections to the ground-shield are:

1. It does not prevent the possibility of an abnormally high pressure existing between low-pressure winding and ground, due to a connection between high- and low-pressure leads inside the case, or in the wiring exterior to the transformer.

2. The ground-shield must be of thin material. With transformers of large size where enormous current may flow in case of a short circuit, it is possible that a portion of the shield may be burned away or that the connection between it and the ground connection may be burned off, thus leaving the high- and low-pressure windings connected, but insulated from ground.

3. The introduction of the ground-shield into a transformer increases its cost, or lowers its efficiency, or both; for the same amount of insulation must be placed between the high-pressure winding and the ground-shield as is ordinarily placed between high- and low-pressure windings; and in addition the ground-shield must be insulated from the low-pressure winding.

4. In transformers there is a leakage magnetic field between high- and low-pressure coils. In that portion of the coils outside the iron this leakage field cuts through the ground-shield, producing eddy currents which may greatly increase the transformer losses. This is particularly true on high-pressure transformers where it is necessary for insulation purposes to make a difference in the lengths of the coils. On such transformers it is necessary to use very thin sheet-metal for the shield, and to slit it at the ends into a number of narrow strips, which are insulated from each other, except at one point.

Conclusions.—Since the ground-shield does not afford absolute protection, and as it increases the cost or reduces the efficiency of the transformer, and on account of the mechanical and electrical difficulties involved in its use, it would seem that for large high-pressure transformers the ground-shield is a theoretical, rather than a practical, means of protection.

It is believed that the grounding of the low-pressure winding at the neutral point is a safer, more practical, and cheaper method of protection than is the use of the ground-shield.

DISCUSSION ON "THE USE OF GROUND-SHIELDS IN TRANSFORMERS."

RALPH D. MERSHON: Undoubtedly, if grounding the neutral of a low-pressure winding does not protect, protection will not be obtained by the use of ground-shields. It seems to the speaker that it is not safe to install a high-pressure transmission system, feeding a city distributing system, without either making use of ground-shields or grounding the neutral of low-pressure windings. Aside from the question of a cross between the high- and low-pressure circuits, it is possible, with everything in good condition, to have electrostatic effects of high pressure on the low-pressure windings, high enough to damage insulators and endanger life. It seems therefore that it is rather unwise to install transformers feeding distributing systems without using one of these means of protection. In some cases the expedient of using spark-gaps between the low-pressure windings and ground is resorted to, and in some cases between the neutral and the ground instead of grounding the neutral. But these spark-gaps are generally the cause of more or less trouble; it is the speaker's opinion that it is much better to ground the neutral permanently.

H. C. WIRT: Transformers having ground-shields were used to a limited extent in this country at a time when the National Board of Fire Underwriters would not permit grounding the secondary. Now that grounding the secondary is permitted, there seems to be no good reason why transformers with ground-shields should be used.

C. E. SKINNER (by letter): In specifying the use of ground-shields between the high-pressure and low-pressure windings in transformers, engineers seek to prevent any possibility of an electrical connection between these windings. The question to be considered is, therefore, whether or not this result can be accomplished.

In the writer's opinion, ground-shields are very undesirable from a constructional standpoint; they do not necessarily accomplish the result for which they are used, and they increase the cost of transformers in which they are used. The writer agrees that the grounding of the low-pressure winding at the neutral point is a safer, more practical, and cheaper method of protection than is the use of the ground-shield. This method gives almost absolute safety, while the use of the ground-shield is at best a doubtful expedient.

P. H. THOMAS (by letter): Mr. Peck has hardly emphasized sufficiently the objections to the use of ground-shields in large high-pressure transformers. That a very efficient protection against the raising of the pressure of the low-pressure winding of transformers, due to a certain class of breakdown, is secured, cannot be denied, but the incidental difficulties and opportunities for trouble introduced through the use of ground-shields far

outweigh its advantages, when protection can be so simply obtained otherwise.

The writer fully agrees with Mr. Peck's conclusions, but wishes to bring out one point: when the grounding of the neutral point of the system is relied upon for protection, there is one weak point. From the nature of the case, the connection between high pressure and low pressure, when occurring on wiring or at the leads of transformers, will be of the nature of a static discharge, also the low-pressure winding of the transformer constitutes a choke-coil between the source of the disturbance and the grounded point; as a result there will be a short-circuit strain impressed upon it of a very severe nature, which may easily cause a breakdown of insulation. This may be avoided by using lightning-arresters as discharge gaps on the leads of the low-pressure winding. This method will not be effective where the connection between high-pressure and low-pressure systems occurs at an intermediate point in the winding of the transformer. Since in this case the transformer is already injured, this fact will not be of such serious consequence.

W. L. WATERS (by letter): A ground-shield undoubtedly affords some protection, but such protection can be obtained in a much simpler and more reliable way by grounding the low-pressure side of the transformer, or by means of some automatic grounding device, such as the Cardew. Considering the question from all points, the writer agrees with Mr. Peck, that the doubtful protection afforded by the ground-shield is obtained at far too high a cost, and that at the present time a ground-shield would be more suitably placed in a historical museum than in a power transformer.

A paper presented at the 188th Meeting of the American Institute of Electrical Engineers, Chicago, June 21-22, 1904.

Copyright 1904, by A. I. E. E.

THE PROTECTION OF HIGH-PRESSURE TRANSMISSION LINES FROM STATIC DISCHARGES.

BY H. C. WIRT.

The various devices for the protection of transmission lines from lightning and other static stresses, made by the leading electric companies, are constantly modified, and it is apparent that improvement in this class of apparatus is needed. The best way to develop such devices is to make a careful examination of the transmission lines and of apparatus that may have been damaged by such high-pressure discharges. It is to be hoped that the following comments on various devices now in use will be of interest, and will bring out discussion of their operation.

Ground-Wires.—Overhead ground-wires have been used in several transmission plants. It is evident that if efficient protection can be secured at the power-house and sub-stations, it is superfluous to use such an overhead wire. If a ground-wire be used, it must be large enough not to break and of material that will stand corrosion; a suitable wire will cost almost as much as an additional transmission wire.

A certain power transmission plant, having three power-houses and seven sub-stations, operating 90 miles of overhead transmission lines at 40 000 volts, has protected the greater part of its transmission system by No. 4 galvanized iron wire placed at the top of the poles, half the length being barbed wire, the other half plain wire,—the wire being grounded at every fifth pole. This wire was installed about 14 months ago; before that time many of the poles had been shattered by lightning, but since then no pole has been damaged, but some apparatus has suffered from lightning, the arc jumping from the trans-

former lead above the oil, in all cases. If lightning-arresters had been placed at all the stations, and no overhead wire used, there would probably have been less damage to apparatus, but the poles would have been shattered. It is not at present the custom to use lightning-arresters on transmission lines, and it is not known whether poles can be protected in any other way than by an overhead ground-wire. It would be of interest to have data upon the frequency of interruption of service of transmission lines on account of poles being damaged by lightning. My opinion at present is that a transmission line can be protected from lightning discharges by suitable apparatus placed in the stations, and that it is not necessary to use ground wires; but an exception will probably have to be made in cases where poles are shattered with great frequency.

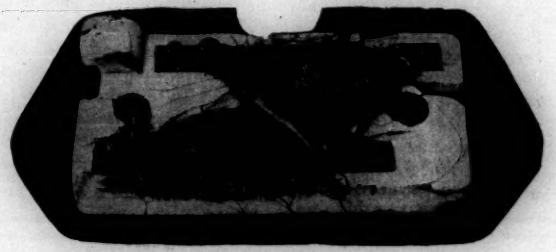
Another installation, operating at 25 000 volts, uses lightning-arresters at stations and sub-stations, with reactive coils, constructed to break down at 50 per cent. above the working pressure, and with a resistance in the ground connection. The arresters have a series of gaps, and are equipped with the "multiplex connection," giving a minimum breakdown distance between line and line. Prior to the installation of this equipment, there was frequent loss of apparatus at the stations, but since, no apparatus has failed on account of lightning, although there have been many severe storms. The management of this plant had begun to equip the transmission lines with a ground-wire, but has decided not to proceed with this plan.

We have in these two cases entirely opposite methods of protecting lines. In one case, the management is so well satisfied with ground-wires that lightning-arresters will not be used; in the second case, the management is so well satisfied with lightning-arresters that ground-wires will not be used. These two plants are in country very similar in its physical characteristics, and are only a few hundred miles apart.

Experience with apparatus damaged by lightning proves that it is as important to provide an easy path for the lightning discharge from line to line as from line to ground. Up to the present, the principal idea in designing a lightning-arrester has been to provide a good path to ground; they have frequently required twice as great a pressure to break down the gap space from line to line as from line to ground. Recently a new type has been suggested called the "multiplex connection," in which a shorter path is provided from line to line, requiring practically

the same breakdown pressure as from line to ground. It is believed that this type will afford additional safety. The photograph herewith shows a particular case in which lightning passing from line to line, jumped across from one terminal to the other of a porcelain primary connection board; to jump this space required 42 000 volts.

Reactive Coils.—Much difference of opinion has existed among engineers on the value of reactive coils, in connection with lightning-arresters. Some recent tests made with the best types of lightning-arresters show that the arresters did not protect the apparatus until reactive coils were used; it seems now that there can be no question that reactive coils are effective, and therefore they should always be used. Although much has been written upon lightning-arresters, there



is little available information upon the relative pressure suitable for the spark-gap; it is difficult to determine just how near to the pressure of the generator a spark-gap can be adjusted without danger of flashing over. When apparatus has burned out, it is possible either to increase the insulation resistance or to decrease the spark-gap distance. Many arresters are now supplied, adjusted for a breakdown pressure only 50% greater than the generator pressure; it can be determined only by experience whether it is feasible to set arresters nearer the generator pressure than this; generators are in many cases insulated to stand only 50% increase above the working pressure, and in this case there is no difference between the breakdown pressure of the insulation and the spark-gap; but the insulation of the machine stands a one-minute test and the static stresses exist only momentarily, which is undoubtedly

the reason that apparatus has not burned out more frequently. Present experience indicates that apparatus, to be safe, should stand an insulation test of 100% greater than rated pressure for one minute; such apparatus may have to be insulated for higher pressure than the present INSTITUTE standard, as it is extremely difficult to protect apparatus unless it will stand the double-pressure test.

Experiments have shown that very high pressures exist momentarily between the outside turns of the coils of a transformer at the moments when it is switched into or out of circuit. Transformers insulated for only 1000 volts per turn will withstand these very high pressures momentarily; as the best modern construction of transformers provides for reenforcing the insulation in the outside turns, thus providing a larger factor of safety, it is a question where the additional protection against breakdown of the outside turns should be provided; a rise of temperature on switching transformers has been noticed in some installations, which is attributed to capacity and reactance, producing resonance, and it has become the practice to provide special means to obviate any rise of pressure due to these causes; such apparatus is known as a "static-arrester." It is necessary only to provide a circuit having a moderate current capacity in order to relieve the line of high pressure, due to these causes.

Discussion on "The Protection of High-Pressure Transmission Lines from Static Discharges."

J. S. Peck: Mr. Wirt says: "Many arresters now are supplied adjusted for a breakdown pressure only 50% greater than the generator pressure." While this adjustment is a measure of the breakdown pressure of the arrester at the generator frequency, it does not necessarily measure the pressure at which the arrester will break down under an extremely rapid change of potential; that is, static discharge. All high-pressure arresters now consist of one or more air-gaps in series with a resistance connected between the line-wire and ground.

Tests have recently been made on a number of these arresters to determine the pressure at which they would break down under two conditions: first, with a current of low frequency, such as is developed by the ordinary alternating-current generator; and secondly, by suddenly discharging a condenser through the arrester. It was found that in all cases the pressure required to break down the arrester under the condenser discharge was very much higher than was required at the generator frequency. With the condenser discharge the pressure was measured by means of a spark-gap shunted around the arrester. By placing the spark-gap around different portions of the arrester, it was found that the greater part of the excess pressure required to break down the arrester under the condenser discharge, was taken up by the series resistance.

It is obvious that if a highly inductive resistance were connected in series with the air-gap, the discharge of a condenser through it would be greatly impeded; and it appears that even the straight carbon-rod resistance offers a considerable amount of impedance to the discharge of a condenser. For this reason the speaker thinks that a statement regarding the breakdown pressure of an arrester under generator frequency is of practically no value as a measure of its protective power against lightning discharges.

Ralph D. Mershon: It is gratifying indeed to know the result of the experiment just cited by Mr. Peck. The writer thinks the result was probably due to the fact that the "non-inductive resistance" was non-inductive in name only.

The question of the accurate adjustment of the striking pressure of arresters is relatively non-important. We do not so much care whether the arresters will discharge at 50 per cent. above the generator pressure, or at 100 per cent. above it, as we do that when they do discharge they will allow to pass sufficient current to keep the pressure of the discharge down to a safe figure and still prevent the generator current from continuing and holding an arc after the discharge has ceased.

Another matter often overlooked in the case of metal cylinder lightning-arresters—a matter which sometimes gives considerable trouble—is the amount of power that they take on

discharge. A 2000-volt arrester with a given number of gaps will take on discharge a given amount of generator current. If on 50 000 volts the number of gaps is increased in proportion to the pressure, the current will be the same on discharge, but the power taken will be about 25 times as great; the result is that if there is a great amount of load on the system there is not enough power left for anything else on the circuit while the lightning-arrester is operating. This condition is especially bad for the operation of synchronous apparatus.

N. J. NEALL: The speaker wishes to take exception to the conclusions drawn by Mr. Wirt—that experience with apparatus damaged by lightning proves that it is as important to provide an easy path for the lightning discharge from line to line as from line to ground.

If we take into account the great distances between the cloud and the line during a lightning disturbance, and the relatively small distances between wires, then, relatively, all wires of any transmission line receive their disturbances as if they were formed of one wire; and it is therefore difficult to see how any difference of potential from this cause could exist between any two wires. It follows that the assumption made—of the necessity for a discharge between wires—does not hold theoretically.

The study and development of protective apparatus during the last eight years emphasize very strongly that certain phenomena occur repeatedly and can be overcome. Generally speaking, if nothing is destroyed in a station equipped with protective apparatus, or if the troubles are comparatively few, the protective apparatus is very highly thought of, although it might turn out that the arresters were really not protecting, and other causes were accountable for relief from lightning disturbances. An excellent plan is to have station operators or line operators record the action of the protective apparatus on their systems, just as they would record the operation of their generators or transformers or any other apparatus which can be metered. A device for this purpose has been suggested, that of using a slip of paper in some of the arrester gaps which would be punctured by discharges. If these papers are removed frequently and systematically doubtless much of the phenomena which we have been studying would have further evidence to substantiate our theories. It is also likely that many troubles would be brought to light that are far more injurious to the normal operation of the line than are lightning disturbances.

Another difficulty is the close setting of spark-gaps to any given pressure. Those who have worked with spark-gaps and spark-gap material know that it is extremely difficult to make measurements and repeat them within five per cent. of the pressure which can be estimated by the ratio of turns. Moreover, it does not seem of such importance in lightning-ar-

resters that we should set our gaps so closely, because if regular apparatus must stand 50% rise certainly any spark-gap can be set to meet such requirement.

F. O. BLACKWELL: Lightning occurs at irregular intervals and in different forms. The kind of arrester which would be best in one lightning storm might be of no value in another. In general, the best we can do is to have a weak point in the system which will allow the lightning to pass through without damaging the machinery. The most primitive form of lightning-arrester, which consists of a grounded pail of water and a wire from the water to the line, furnishing a constant leak to ground, is very effective.

H. C. WIRT: A type of lightning-arrester used in Switzerland and Italy consists of a jet of water turned on the line, so that the line will be discharged through the stream of water. Neither the water-stream arrester nor the horn arrester will take a sufficiently large discharge to relieve the line properly. The principal difference between these arresters and those of American design is in the number of gaps employed. The water-stream arrester with a single gap could be used but the water would have to be of high resistance to prevent an arc holding.

We have not tried either of these lightning-arresters but we intend to do so. The question of the amount of current that an arrester should be designed to take is undetermined. If the resistance used in the arrester is low the current that would follow after a lightning discharge may be large enough to shut down the plant; if the resistance is too high the lines may be only partly relieved and the lightning may then go through some transformer. We should of course consider the lightning-arrester in theory but we should also have extensive tests of arresters under service conditions. The speaker means that no one should decide for or against the use of a ground-wire unless he has been at places where such wires are in use.

R. F. HAYWARD (by letter): The writer believes that it is the apparatus, not the pole-line which needs protection from lightning. If poles get shattered frequently it may, as is pointed out, be necessary to use a grounded wire, but steel construction would be a better remedy.

The transmission lines in Utah, consisting of 300 miles of 40 000-volt pole-line and 125 miles of 28 000-volt line are situated at the base of the Wasatch range where the thunder-storms almost invariably break. These lines are particularly liable to be affected by lightning, and every thunder-storm manifests itself in some way. It is seldom, however, that poles are struck, though there have been several cases of shattered insulators and splintered poles. With duplicate lines the striking of a pole should cause but a short interruption, and the damage is easily repaired. But if the transformers are damaged a whole station may be temporarily disabled,

and the damage is costly. When a pole-line is struck a wave is set up which finds its vent in a lightning-arrester, breaks itself against a transformer coil or breaks down the coil. If the insulation of the coil stands the shock and there is no lightning-arrester discharge, an arc may form from terminal to case. Experience seems to show that a lightning discharge has the greatest effect on the station nearest to it, but that the horizontal discharge, occurring between clouds and more or less parallel to the lines, produces some of the most severe shocks at lightning-arresters or transformers. In the neighborhood of Salt Lake City it seems that there is a greater tendency to horizontal discharges between clouds than to lightning discharges direct to ground. This is doubtless due to the abrupt rise of the mountains from the level of the valley. There is no doubt that lightning can and does induce very high pressure waves between wires, many instances having occurred in Utah. Protection should therefore be provided against this.

The writer is in doubt about the use of reactive coils, as there are instances which show their value, and others which do not. It seems that a reactive coil to be effective must be pretty large. It has occurred in the writer's experience that a pole has been struck with lightning and at the same instant a discharge has occurred from transformer terminal to case, while there was no discharge over lightning-arresters, although a reactive coil was in circuit.

Instances showing that a transformer coil or the windings of an armature act as a " breakwater " to the passage of high-frequency waves are too numerous to mention. One instance is interesting. One of the 2000-volt circuits supplying Ogden City is lead from the power-house through booster transformers. A severe storm occurred when the boosters were not in circuit and a discharge took place across the collector rings of one of the armatures in the power-house. A few days later a similar storm occurred when the boosters were in circuit and one of them was burnt out.

The writer believes that reactive coils of comparatively cheap construction should be put in to satisfy the conscience of the engineer, but for real protection the money should be spent on the transformer. An 80 000-volt transformer working on a 40 000-volt circuit and protected by a 40 000-volt lightning-arrester ought not to break down. The writer's opinion has changed somewhat during the past year in this matter and he now believes that any reactance coil of large capacity introduces some extra apparatus and additional wiring, whereas the same money spent in the transformers themselves ought to provide sufficient insulation to stand these shocks.

The writer believes that lightning-arresters should be adjusted so that they are near the limit of their own safety; plenty of spare parts should be provided and an occasional burnout

of the lightning-arrester resistance should be accepted as proof that the lightning-arrester is giving some protection. Anyone can put so many gaps and so much resistance in an arrester that it will never burn out, but it does not follow that this arrangement affords any protection.

P. H. THOMAS (by letter): Static discharges in high-pressure transmission lines arise from two causes: first, abrupt changes of potential caused by switching or accidents in the transmission system itself; secondly, lightning.

The best protection against the first class, which are certain to be quite numerous, is in providing ample insulation in the design of the plant, not so much in the heavy thicknesses of the solid insulating material, which is exceptionally strong to resist static strain, as in the air distances, oil distances, and surface distances between exposed points. In the opinion of the writer, it is extremely important that these distances be ample. For instance, they should be laid out to stand with certainty double the normal pressure of the system, since probably in very few cases would static pressures exceed this limit, except of course in case of lightning. It is true that pressures of startling magnitude are occasionally reported from transmission plants, but in few cases have the existence of such been clearly proved, and in many cases the reports have proved to be unfounded.

In laying out surface distances and air spaces, it must be remembered that the jumping power of high pressures increases much more rapidly than the pressure itself. Distances should not be doubled for double pressure but a curve of actual tests should be used. It must be remembered as well that surface distances have their insulation strength much deteriorated by a deposit of moisture or of conducting dust, and that some kinds of material, notably hard rubber, may have a gradual deterioration. It must also be noted that the jumping distance over a surface is much affected by the presence near that surface of another conductor at a different pressure. For example, a wire within a bushing, and the presence of such a conductor, in extreme cases may increase by several times the jumping distance of a given pressure. *This fact is very well established and has been given entirely insufficient recognition in laying out surface distances for insulation.* Still another factor weakens the insulation strength of surfaces when subject to static discharges; namely, the fact that for an abrupt change of pressure a considerable quantity of electricity must flow at the time of the application of strain to charge up the surface of the insulation near the charged conductor, and this flow of current momentarily weakens the total insulation strength of the surface.

It appears to the writer that since a great mass of data with regard to the effect of ground-wires or other devices on the elimination of troubles due to lightning is required to eliminate

the effect of conditions other than those being studied, that little can be gained from the consideration of one or two cases of ground-wires, and that all our accurate data furnish an insufficient basis for conclusions at the present time. It seems unlikely that even though the grounded wires may be proved to have protective effect, as they undoubtedly do, they will ever be of general use, in view of the mechanical and electrical difficulties and expense involved. As Doctor Perrine has stated, there is a tendency where ground-wires are brought near to high-pressure conductors, for current to be set up in the ground-wires, causing more or less energy loss and possibly other difficulties. Furthermore, there is an increase of electrostatic capacity, due to the presence of ground-wires in the neighborhood of the high-pressure conductors. These objections may be much less critical on low pressure, short-distance plants. In some such plants ground-wires may turn out to be the best ultimate protection.

Experience shows that direct strokes of lightning must be expected on transmission lines in most localities. Unless grounded guard-wires are used, these strokes must inevitably injure poles. Such injuries, however, often do not cause a shutdown of the plant. It is highly desirable for these severe discharges to get to earth as quickly as possible.

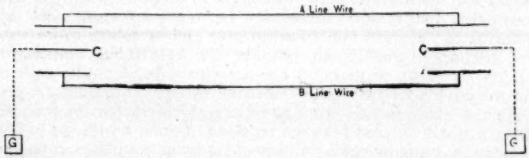
Arresters in the station constitute the most approved practice and will be relied upon in most cases. In very important high-pressure plants, however, it would seem that where regular attendance is feasible a set of arresters at a point from one-half a mile to two or three miles from the station would be a very desirable precaution. In such cases where constant attendance is not feasible, but where there is a suitable location for arresters, the use of fuses, possibly arranged so that when one blows another comes into service, would be satisfactory. In such cases, should trouble occur at the arresters, the line would clear itself immediately.

Reactive coils may serve two functions: the prevention of short-circuit strains between the turns of windings, for which purpose they are especially suited, and to assist the discharge of lightning-arresters to ground by delaying the rise of pressure of a transformer terminal at a time of static disturbance. In either case the protection derived from the reactive coil is a matter of degree, depending upon the relative electrical characteristics of the transmission line, the windings of apparatus, the arresters, and the pressure of line. A given coil may be very effective on one circuit at one pressure, and entirely inadequate for another circuit on another pressure. A freely-discharging arrester on a line of small electrical capacity, protecting apparatus itself having a large electrostatic capacity near its terminal, would require comparatively the smallest choke-coil for restraining the ultimate rise of potential above ground. An arrester with a ground-

connection on a line of large electrostatic capacity and high-pressure, where the apparatus to be protected has a comparatively small electrostatic capacity near the terminal, would require a coil very many times more powerful to obtain the same protection to ground than the coil of the first case.

For the protection against short circuits in windings, the choke-coil must be proportioned in its choking power to the number of turns, etc. and the winding itself, at least approximately; and to be effective without being unduly large can oftentimes be advantageously assisted by the use of a condenser connected between the terminal of transformer and ground. It would seem evident from the above that reactive coils should be of a power adapted to the circuits upon which they are to be used.

N. M. SNYDER (by letter): On the assumption that the line-wires of a transmission line have capacity, it might be said that when we use an overhead ground-wire as suggested, the nature of the protection afforded seems to be due to the static charges surging from the line-wires to the ground-wire, as evidenced by the jumping of the arc across the transformer leads above the oil. This shows capacity in the circuit. The writer concurs with Mr. Wirt in saying that we should be able to protect stations and apparatus without resorting to the use of the ground-wire. If we make the same conditions at the station as existed when the grounded line was used, it should be of material benefit. If we connect a plate or series of plates,



equal in capacity to the wire to be protected, at the power-house and sub-station and do this with all wires, arranging them symmetrically and equidistant from a central or ground-plate of equal area, should we not have an ideal static arrester? As long as the wire or wires are balanced and current is flowing equally in all, no interference should be experienced in retardation by the ground-plates, nor any serious faults from resonance. A static disturbance occurs; it surges from wire to wire as through a condenser; the ground-plate is neutral to the plates of the wires; so any charge of static on either wire will promptly be communicated to the ground-plate and relieve the strain. Of course in adjusting the plates care should be taken to have them sufficiently separated to exceed 25 per cent. higher pressure than that of the generator. This

will prevent the breaking down of the air-gap, the principle being to make a static line balance normally; and when any excess of static occurs it is quietly induced to earth in an efficient manner by making use of the condenser principle.

JOHN PEARSON (by letter): There is one point in regard to the grounded wire with which the writer thoroughly agrees. The writer considers that the grounded wire cannot well be used: first, on account of cost; secondly, because with this wire a short circuit may easily be established; thirdly, because it does not afford complete protection to apparatus at generating or distributing stations. For more than three years the writer has been with a company operating a 4000-h.p. power-plant (not using the grounded wire) located near Somerset, Wis. This plant transmits current to St. Paul, 28 miles distant, at 25 000 volts pressure. During this time only three poles were split so that they had to be removed, but not so badly as to interfere with the operation of the plant. Another plant, only four miles distant, with a pole-line running through a hilly country, and not using the grounded wire, has not suffered at all from poles being shattered by lightning; but it has suffered a great deal from lightning, due to inefficient lightning-arresters.

From this and other data, it seems that lightning- and static-arresters can be arranged so as to be of more protection than the grounded wire. Experience proves it necessary to provide: first, an easy path from line to ground, through which the line wires may be relieved of high pressure in respect to the ground; secondly, to provide choke-coils between arresters and apparatus to be protected, so as to give the arresters more time to discharge; thirdly, to provide the multiplex connection which Mr. Wirt suggests on the arrester side of choke-coils so as to provide an easy path from line to line; fourthly, to provide the high-pressure winding of transformers (or generators) with a static by-pass between sections of such windings. This is done by bringing out a number of leads, at equidistant points, from the high-pressure winding of a transformer or generator to be protected, to provide metal knobs and series resistance between these leads, so that normally this combination is a non-conductor, but at say 50% increase in pressure across a section this combination becomes a conductor, and relieves the particular section which it is designed to protect.

The writer knows that when the lightning-arresters which are connected to the *line side* of choke-coils discharge, great differences of pressure are set up between wires on transformer or generator side of choke-coils. This difference of pressure frequently causes a flash from lead to lead in transformer top, and sometimes will break down the insulation between layers in transformer coils, especially the layers next to line wires. An efficient remedy for this is to provide an easy path for the discharge outside of the transformer top,

by bringing out leads and joining as suggested above. One feature about connecting a static by-pass over successive sections of the winding is that it will take no more pressure to break down all the air-gaps across the whole transformer winding than it will take to break down the air-gap across a single section, owing to the fact that all the gaps are not broken down at the same instant. This idea in transformer protection has been used for over two years at St. Croix Power Co.'s

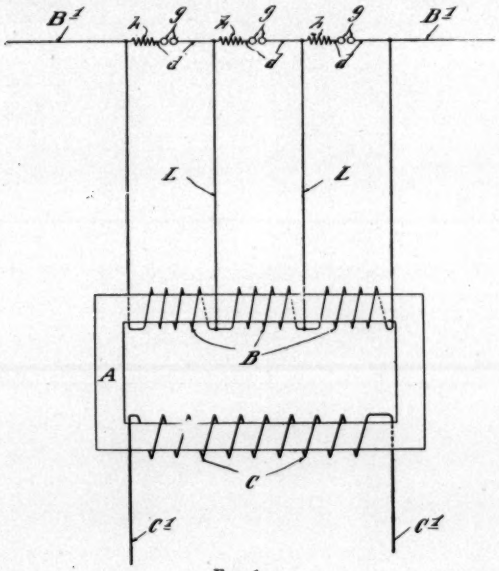


FIG. 1.

plant, Somerset, Wis., and has also been installed at a new plant in New York State.

Prior to using this form of protection for transformers, the St. Croix Power Co. lost four transformers in one season, caused by static jumping from lead to lead in transformer top; since then there has been no loss from similar causes. In Fig. 1, *A* represents the core of a high-pressure transformer; *C* the low-pressure winding; *C'*—*C'* terminals of this winding. *B* represents the high-pressure winding; *B'*—*B'* represent the terminals of this winding. Leads *L*-*L* are brought out between

terminals of this winding, dividing it into three sections in regard to static-arrester, and between these leads are provided non-inductive resistance, *k*, metal knobs, *g*, with their air-gap, also wire (or conductor) *d*.

Fig. 2 shows this scheme connected to a high pressure generator with revolving field. The connection is the same as in

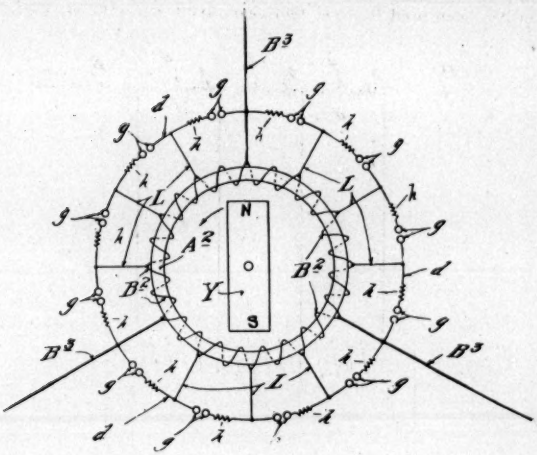


FIG. 2.

Fig. 1. Referring to Fig. 1, it can easily be seen that there exists great strains between *B'-B'*, due to lightning arresters discharging or other causes (this charge being of an oscillatory nature); each one of the air-gaps is broken down successively, one after the other, and it will take no more strain to break down all the air-gaps than it will take to break down a single gap.

ANSWERS TO QUESTIONS RELATIVE TO HIGH-TENSION TRANSMISSION.

The answers to questions printed in this report have been gathered from authoritative sources. These answers indicate present electrical engineering practice; but it should be understood that the Institute merely transmits the information contained in the answers, and that neither the Institute nor the Committee on High-Tension Transmission assumes any responsibility as to its correctness or its reliability as a guide to best engineering practice.

At a meeting of the Board of Directors of the AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS, held September 26, 1902, it was

"RESOLVED, That a Committee on High-Tension Transmission, consisting of five members, may be appointed for the purpose of collecting data respecting present practice in electric transmission at high voltage and of presenting a report which will indicate the successful methods which are now in operation in such form as to be of immediate value to electrical engineers. It is within the scope of the Committee to secure data upon line construction, insulators, pins and the like, and the conditions of operation at different voltages and under different climatic conditions; to investigate methods of testing insulators and to indicate the method or methods which in its judgment are superior. Also to ascertain the methods employed for voltage regulation, the conditions attendant upon the switching of high-tension circuits and to collect data respecting lightning and static disturbances and the use of grounded protective wires."

In accordance with this resolution the Transmission Committee prepared a list of questions, copies of which were sent to those connected with and operating transmission plants, with the request that the answers to the questions be filled in and the lists returned. Although the number of replies received fell far below the number hoped for, a considerable amount of information was obtained. The following matter presents in condensed form the answers received. For convenience in presentation, the plants have been classified with respect to the voltage of transmission.

Total number of plants that have filled out lists to date, 47. These plants are classified as follows:

Class A. Plants transmitting under 12 500 volts.
B. Plants transmitting from 12 500 to 19 000 volts.
C. Plants transmitting from 20 000 to 24 000 volts.
D. Plants transmitting from 25 000 to 29 000 volts.
E. Plants transmitting from 30 000 to 39 000 volts.
F. Plants transmitting from 40 000 to 60 000 volts

I. LINE IN GENERAL.

3. *What is the distance of transmission?*
4. *What is the transmission voltage at the generating end and at the receiving points?*
5. *Is the transmission single-phase, quarter-phase (two-phase), or three-phase?*
6. *What is the frequency?*
7. *How much power is transmitted?*
8. *What is the average power-factor at the generating station and at the sub-stations?*
14. *What is the distance between conductors?*

(For answers to these questions see Table A.)

TABLE A.

Class.	Number of plants.	Transmission voltage.			Total mileage of transmission lines.	Total power transmitted in kilowatts.	Length of Lines in miles.			Phase			Frequency, cycles per second.						Range of power-factor	Distance between conductors in inches		
		Maximum.	Minimum.	Average.			Maximum.	Minimum.	Average.	Single	Two	Three	25	30	33	50	60	66		Maximum.	Minimum.	Average.
A	19	12 000	4 600	8 000	217	31 135	25	3	9.5	1	4	14	2	1	2	—	14	2	80 to 100	36	14	19
B	7	16 000	14 500	15 000	297	65 425	31	7	23	—	—	7	2	1	—	1	3	—	80 to 97	40	18	27
C	9	24 000	20 000	22 600	394	64 999	60	107	32	—	—	9	2	1	—	—	5	1	80 to 90	48	26	33
D	4	27 000	25 000	25 500	127.50	23 400	46	16.6	32	—	—	4	—	—	—	—	3	1	80 to 90	50	18	39.5
E	4	34 000	30 000	31 300	276.30	18 825	83	29	62	—	—	4	1	—	—	1	2	—	90 to 95	40	24	31
F	4	60 000	40 000	51 600	328.25	14 875	101	60	75	—	—	4	—	1	—	—	3	—	65 to 100	108	42	76

12. *How many complete circuits are there on each pole line?*
13. *What is the standard distance of the lowest conductors above the ground?*
15. *What length of span is standard?*
16. *What is the longest span used with standard construction or modification of it?*
24. *What is the greatest deflection of line ordinarily allowed on a single angle-pole?*
25. *Do angle-poles have double fixtures?*
26. *Are angle-poles braced or guyed? If guyed, at what point relative to the power wires are the guys attached? (A sketch is desirable.)*
27. *What is the normal length of span between angle-poles?*
28. *If guys are used, do you use strain insulators in the guys?*
32. *Are the power wires transposed? If so, how many times and at what intervals of distance?*

(For answers to these questions see Table B.)

TABLE B.

Class.	Max. no. of complete circuits on one pole line.	Height lowest conductor is above the ground in feet.	Standard length of span in feet.	Longest span with standard const. feet.	Max. deflection allowed on ordinary single pole (horizontal.)	No. of plants using double fixture on angle-poles.	No. plants that guy or brace angle-pole.	Length of span between angle-poles.	No. of plants using strain insulators in guys.	No. of plants that transpose lines.
A	9	18 to 40	80 to 125	100 to 240	10° to 90°	17	15G. 2G&B	50 to 130	11	8
B	3	15 to 32	80 to 125	100 to 175	10° to 60°	6	7G	20 to 100	6	5
C	2	15 to 27	90 to 140	100 to 300	12° to 30°	9	3G 2B 4G&B	12 to 100	4	8
D	2	25 to 35	90 to 130	125 to 200	15° to 45°	4	1G 2B 1G&B	50 to 90	2	3
E	2	19 to 27½	100 to 130	360 to 400	45°	3	3G 1B	80 to 120	1	4
F	1	19½ to 30	100 to 180	200 to 320	10°	1	1G 1G&B	110	0	4

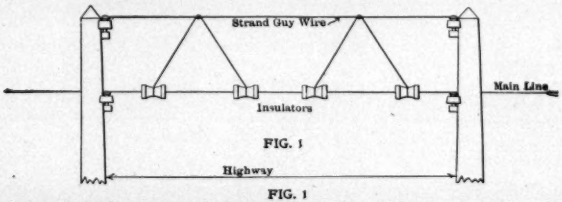


FIG. 1

18. *What heavier construction, if any, is used on such spans?*
19. *What is the longest span of any kind?*
20. *What is the distance between wires on this span?*

GENERAL DESCRIPTION OF CONSTRUCTION USED IN EXTRA-LONG SPANS.

Spans to 300 feet: the poles are usually double cross-armed and guyed; in some cases double poles are also used.

Span 626 feet: double poles, double cross-arms guyed two ways, and wires were spaced eight feet apart.

Span 800 feet: double poles and 6 by 6 in. cross-arms, poles guyed with steel cable two ways.

Span 586 feet: six poles, two poles for each wire, a cross-arm bolted on top of each pair of poles with four insulators in it; the six poles are framed together and braced in all directions.

Span 1750 feet: two poles set 10 feet apart, 66 feet high, 10-in. tops, ¾-in. steel cable was used on this span, it being constructed to take the place of a pole line across a dry river bed in case of washout. Factor of safety is only 1.6 on this span and has withstood winds of 90 miles per hour. It is supported by compression strains on insulators whose pins stand radially around the beam; six feet between wires.

Span 400 feet: four poles set same as a tower and held together, also guyed; double cross-arms, wires spaced four feet apart.

34. *Do you consider transposition necessary so far as the power line itself is concerned? If so, why?*

35. *Do you consider the transposition of the power lines necessary for the protection of adjacent telephone and telegraph wires?*

REASONS FOR TRANSPOSING POWER LINE.

One company thinks transposing of power lines is not necessary for lines up to 30 miles and voltages under 20 000, but for distances and voltages in excess of these, thinks it better as power wires are more symmetrically located as regards the earth.

One company does not think transposing is necessary when synchronous converters are used at intervals along the line.

One company thinks it is decidedly necessary to transpose power lines, their principal reasons are; the lack of interference with telephone and telegraph wires running parallel, and the more spiralling, the less apparent impedance.

Another company does not think it necessary to transpose power lines when there is only a single line on poles; they think it is advisable if not absolutely necessary to transpose power lines as a protection to adjacent telephone and telegraph lines.

Out of 23 companies that express opinions on the necessity of transposing or not transposing the power lines so far as the power line itself is concerned, 15 think it is not necessary, and nine of the 20 think it is not necessary to transpose power lines as a protection to adjacent telephone and telegraph lines.

29. *Are braces used on the cross-arms? If so, of what material and how constructed? (A sketch is desirable.)*

30. *How are the cross-arms attached to the poles, and how deep are poles gained?*

METHODS OF BRACING AND FASTENING CROSS-ARMS TO POLES.

Class A.

Majority of cases, strap-iron braces 1¼ by ¼ in. are used.
In one case angle-iron braces are used.
In three cases strap-iron galvanized braces are used.
In one case no bracing is done.
In eleven cases through bolts are used to fasten cross-arm to pole.
In six cases lag-screws are used to fasten cross-arm to pole.
Through bolts average from ⅝ to ¾ in. in diameter.
Poles are gained from ½ in. to 3 in. deep.

Class B.

Strap-iron braces are used in all cases.
In one case the strap-iron braces were galvanized.
In four cases through bolts were used to fasten cross-arm to pole.
In three cases lag-screws were used to fasten cross-arm to pole.
Gains ½ in. to 2 in. deep.

Class C.

In two cases wooden braces are used.
In three cases strap-iron braces are used.
In one case strap-iron braces were galvanized.
In two cases 1¾ by 1¾ angle-iron braces were used
In two cases no braces were used.
In seven cases bolts were used to fasten cross-arms to poles.
In one case bolts were galvanized.
In two cases lags were used, average ⅝ in. to ⅝ in. diameter.
Gains ⅝ in. to 1½ in. deep.

Class D.

In two cases strap-iron braces were used.
In one case no braces were used.
In two cases through bolts were used to fasten cross-arms to poles.
In one case ½ in. lag screws were used to fasten cross-arms to poles
Gains ¾ in. to 1 in. deep.

Class E.

In three cases strap-iron braces were used.
In one case only one brace used on each cross-arm.
In one case strap braces were galvanized.
In one case angle-iron brace on one side of cross-arm.
In three cases ¾ in. through bolts were used.
In one case lags screws were used.
Gains ½ in. to 2 in. deep.

Class F.

In three cases no bracing done.
In one case white oak ¾ in. by 3 in. was used.
In one case cross-arms were mortised through pole.
In one case two ⅝ in. bolts were used.
In one case two ⅝ in. lags screws were used.
Gains 1½ in. deep.

(See sketches showing various arrangements of conductors on cross-arms, p. 601-604

37. *In crossing other power lines, telegraph or telephone lines, railroads or highways, are there any special precautions taken against the danger of the power lines breaking and falling? If so, what?*

VARIOUS METHODS OF CROSSING OTHER POWER LINES, TELEPHONE OR TELEGRAPH LINES, AND RAILROADS AND HIGHWAYS.

Class A.

1. Extra cross-arms and idle wires.
2. Double pole fixtures and short spans.
3. Guard wires underneath power wires.
4. Extra-high poles.
5. A ground net of ¼ in. steel cable suspended across railway right of way under power wires and six feet below them.

Class B.

1. A grounded network of iron wire under power line.
2. Extra-high poles.
3. Telegraph lines put under ground.

Class C.

1. Guard net under power wires.
2. Truss bridges built across railway track upon which power wires are supported.
3. Guard wires placed over telegraph wires.
4. High poles.

Class D.

1. Short spans and double fixtures.
2. High poles placed eight feet apart, telephone line passes between.
3. Bronze cables used over railway crossing.
4. Telegraph wires put in cable underneath.

Class E.

Guard wires.

Class F.

1. Twelve foot span and high poles.
2. Guard wires.
3. A grounded net made of ⅜ in. steel cable suspended between poles over railway right-of-way about six feet under power wires.

40. *Are there automatic overload devices arranged for cutting off the individual sub-stations from the power line?*

The following automatic overload devices are used for cutting off the individual sub-stations from the power line:

Class A.

Four plants use high-tension fuses.
One plant uses high-tension fuse-switch operated by hand.
Two plants use automatic oil-switch.

Class B.

One plant uses high-tension fused cut-outs.
One plant uses fuse-switch.
One plant uses air-brake circuit-breakers.

Class C.

One plant uses fuse circuit-breaker.
One plant uses oil-switch.
One plant uses oil circuit-breaker.
One plant uses automatic circuit-breaker.

Class D.

None.

Class E.

One plant uses fuses.
Two plants use fuse-switch.

Class F.

Two plants use oil-switch.
Two plants use fuse.

41. *Are the intermediate sub-stations sources of much trouble? If so, what?*

VARIOUS SOURCES OF TROUBLE AT INTERMEDIATE SUB-STATIONS.

Class B.—One company had trouble with their rotaries but had cross-circuiting rings put between each armature section. O.K. now.

Class C.—One company had endless trouble with double-current generators; armatures burning out. One company has had trouble due to defective switching apparatus.

43. *How are the wires carried into the power house and into the sub-stations? (A sketch is desirable.)*
44. *How is the support arranged just outside of the building, and just inside of the building? (Sketch.)*

(See sketches showing various methods of bringing lines into power houses and sub-stations Figs. 2–15.)

45. *Do you have switches located outside to cut the wires entirely clear of the sub-stations?*

No. of plants that have switches located outside to cut the wires entirely clear of sub-stations.

Class	A	B	C	D	E	F
	8	0	3	0	1	1

II. CONDUCTORS.

47. *Of what material are they made?*
48. *Are they solid or stranded? If latter, how many strands or separate wires?*
49. *If of copper, are they hard drawn, medium drawn, or soft drawn?*
50. *Are they bare or insulated?*

KIND OF CONDUCTORS.

Class A.

Six plants use solid copper hard drawn.
Seven plants use solid copper medium drawn.
Four plants use solid copper soft drawn.
One plant uses 19-strand aluminum.
One plant uses 7-strand aluminum.
Twelve plants use bare conductors.
Seven plants use waterproof insulated conductors.

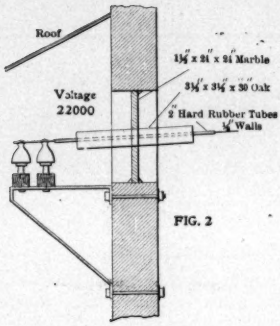


FIG. 2

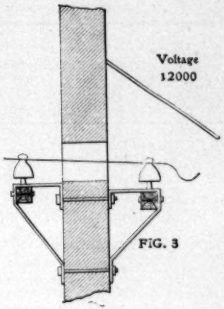


FIG. 3

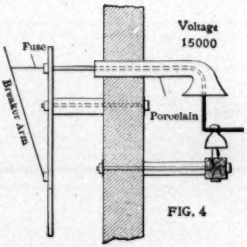


FIG. 4

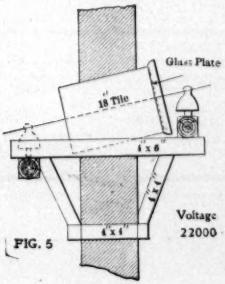


FIG. 5

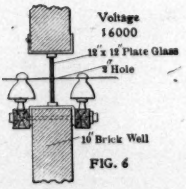


FIG. 6

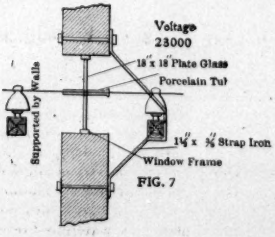


FIG. 7

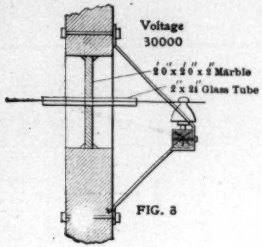


FIG. 8

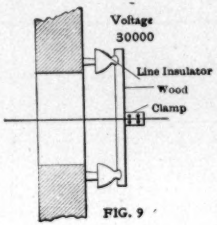


FIG. 9

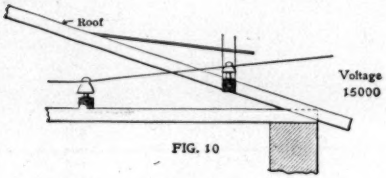


FIG. 10

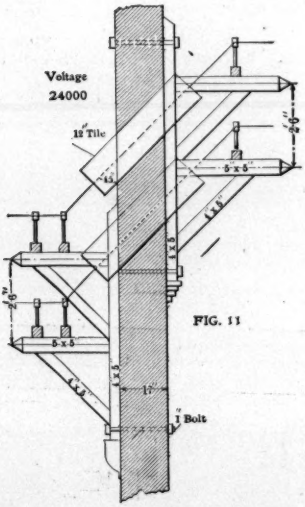


FIG. 11

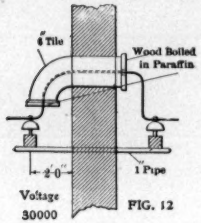


FIG. 12

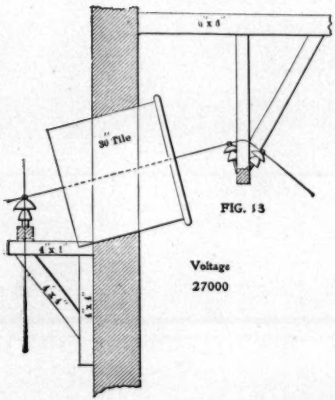


FIG. 13

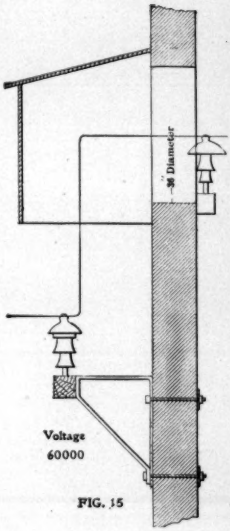


FIG. 15

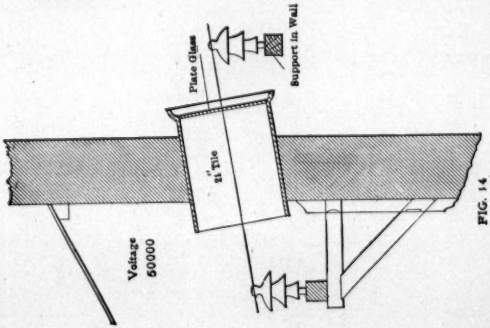


FIG. 14

Class B.

Two plants use solid copper hard drawn.
Two plants use solid copper medium drawn.
Two plants use solid copper soft drawn.
One plant uses stranded aluminum.
Five plants use bare conductors.
Two plants use waterproof insulated conductors.

Class C.

Three plants use solid copper hard drawn.
Three plants use solid copper medium drawn.
Three plants use stranded aluminum.
All plants use bare conductors.

Class D.

One plant uses solid copper hard drawn.
One plant uses solid copper medium drawn.
One plant uses solid copper soft drawn.
One plant uses 7-strand aluminum.
All plants use bare conductors.

Class E.

One plant uses 7-strand copper soft drawn.
One plant uses solid copper medium drawn.
Two plants use 7-strand aluminum.
All plants use bare conductors.

Class F

Two plants use solid copper medium drawn.
One plant uses solid copper hard drawn.
One plant uses solid aluminum.

51. *Have you had any serious amount of corrosion of conductors due to any causes? If so, what are the causes?*

Only two plants have experienced trouble with conductors corroding; viz., one company has one sub-station at a chloridizing quartz mill; the gases corrode the copper and cover the glass line-insulators with a film. The other company has its copper lines corroded by chemical fumes.

52. *If the conductors are aluminum, have you found them satisfactory? If not, why?*

One company experienced a great deal of trouble with their solid aluminum line; cause being that the aluminum crystalized due to the continuous vibration, and used to break frequently.

53. *Is high-tension wiring inside of buildings done with bare or insulated wire, and if the latter, what kind and thickness of insulation?*
54. *What kind of insulators are used for this interior wiring?*

The majority of plants use rubber-insulated wire for their interior wire (high tension) the thickness of rubber varying from $\frac{3}{32}$ in. to $\frac{1}{2}$ in. The balance use bare wire, with the exception of four or five plants which use paper or rubber lead-covered cable laid in ducts. The interior wiring in classes A and B is held on porcelain cleats and knobs in the majority of installations. In classes C, D, E, and F the ordinary line insulator is generally used to support the interior high-tension conductors.

III. LINE INSULATORS.

55. *Are the insulators glass or porcelain?*
56. *What is name of maker and what is the trade name or designation for them?*
57. *Have you any preference as to material and if so, why?*
58. *If porcelain, are they tinted, and what color?*
60. *Are the wires carried upon the top or the side of the insulators?*
61. *What tests were given the insulators before installing?*
62. *At what voltage will a flash occur between wire and pin when being sprayed with water?*
63. *At what voltage will they puncture?*
64. *Have you found your insulators satisfactory, if not what has been the trouble and to what has it been due?*

TABLE C.

Class.	Material.			Color.		Method of Tying.		Tests.		Makers.
	Porcelain.	Glass.	Porcelain and Glass.	White.	Brown.	Side of Insulator.	Top of Insulator.	Puncture Volts.	Spray Volts.	
A	6	9	3	7	2	6	11	20 000 to 50 000	—	R. Thomas & Son Co. Hemingway Glass Co. Imperial Porcelain Works. C. S. Knowles. P. Locke & Co. General Electric Co. Redlands Co. Guion, Italy.
B	2	4	1	3	1	4	2	40 000 to 50 000	25 000	
C	4	4	1	3	3	4	3	50 000 to 75 000	—	
D	2	2	—	1	1	2	1	80 000 to 120 000	—	
E	4	0	0	4	0	4	0	60 000 to 90 000	35 000 to 55 000	
F	2	1	1	1	1	1	1	120 000 saltwater	70 000	

Notes.—Prefer porcelain to glass on account of greater mechanical strength; greater dielectric strength; less liability to creeping of static over surface.

Prefer glass to porcelain on account of defects being easier detected by inspection; less tendency for dirt to hold on.

Four companies had trouble with tops breaking off glass insulators at grooves, due to changes in weather, etc. Two companies had trouble with glazed filled insulators, the insulator cracking at the joints.

One company had trouble with film forming on glass insulator from quartz mill.

IV. CROSS-ARMS.

65. *What are the dimensions of the cross-arms?*
66. *Of what material are they made?*

Sizes vary from 2¼ in. by 4¾ in. to 4½ in. by 9 in., the average section being 3½ in. by 4½ in.

The majority of plants use yellow pine, other woods used are: white pine, yellow fir, Oregon pine, spruce, Oregon fir, peroba, and cabreura, the last two being Brazilian woods.

67. *If of wood, have they been treated in any way? If so, in what way?*

The following are different methods of treating cross-arms:

(1) Painted with white lead.
(2) Painted with mineral red in oil.
(3) Painted two coats.
(4) Painted coal tar.
(5) Painted two coats metallic paint.
(6) Treated with carbolinium.
(7) Boiled in linseed oil two or three hours.
(8) Dipped in bitumen paint.
(9) Dipped in creosote.

V. POLES.

68. *What kind of poles? Steel or wood? If wood, what kind?*

Majority of plants use cedar poles. Other woods used are: chestnut, juniper, cypress, red cedar, tamarack, Idaho cedar, spruce, and white cedar.

71. *What are the dimensions of the tops of the different lengths of poles, also the minimum diameter of the butts?*

Tops vary from 5 in. to 8 in. in diameter.
Butts vary from 9 in. to 24 in. in diameter.
Average top is 7 in.; average butt is 12 in.
} Poles vary from 25 ft. to 45 ft. long.

72. *How deep are the different lengths of poles set into the ground?*

Poles are placed in ground from 4 ft. to 8 ft. according to their length and condition of soil.

Poles were treated in the following ways:

74. *Are the poles treated in any way? If so, how? Are they painted?*

(1) Gains painted with metallic paint.
(2) Butts tarred.
(3) Poles painted.
(4) Butts painted.
(5) Tops painted.
(6) Butts treated with carbolinium.
(7) Tops painted with linseed oil.
(8) Butts burned and tarred.
(9) Butts painted with asphaltum.

75. *How are the tops finished?*

Majority of plants roof the tops of the poles.
A large percentage paint tops of the poles.

One plant puts cast-iron caps on poles.

One plant champfers the pole tops to pin that is in end of pole, and binds No. 6 galvanized-iron wire around end, and paints top with P. & B. paint.

76. *Is there a pin in the top of the pole, and if so, is there a metal band around the top?*

Four companies that have pin in top of the pole have an iron ring around pole.

One company uses a composite pole made with a 7-in. iron pipe, socket 13 ft. long, Australian jarra wood top 7 by 7 in., 17 ft. long, pressed into the socket; this pole is placed 6 ft. in the ground. Poles are tarred, and a galvanized-iron cap is put on top of pole. A few companies use octagonal and square poles.

Kind of Wood.	Location.	Life of pole in years.
Red Cedar	Ohio	20
Cedar	Oregon	10–15
"	California	10–15
"	Idaho	15
"	Montana	6–7
"	Washington	10–15
"	Minnesota	14–16
"	Pennsylvania	9
"	Canada	15
Chestnut	New York	8–14
"	Pennsylvania	8
"	Massachusetts	8–12
" (2d growth)	Pennsylvania	12–16
Juniper	Georgia	15
Cypress	Carolina	8
Tamarack	California	5
Pine	Pennsylvania	8

69. *What is the length of their life and on what peculiar conditions, if any, does this depend?*

78. *Give dimension sketches of pole-head, showing cross-arms, pins, and insulators.*

See dimension sketches on pages 601-604

73. *Are any of the poles set in concrete or otherwise, giving additional solidity in the earth?*

The following methods are used for poles in boggy or swamp land:

1. Set in concrete.
2. Tamped with broken stone.
3. Protected by rock cribs.

VI. PINS.

79. *Of what material are the pins made?*
80. *If of wood, what kind of wood?*

Classes A, B, C, and D.

In these classes the standard 1½ in. locust pin is used in most cases; other kinds of pins used are: black locust, oak, eucalyptus, hickory, iron with wooden thimbles, porcelain, and iron ⅝ in. fastened into insulators with cement.

Classes E and F.

Following kinds of pins are used:

1. Iron pins held into insulator with Portland cement.
2. Iron pins, wooden thimble, porcelain base.
3. Locust and eucalyptus.
4. Steel pin and cast-iron bushing in cross-arm (see sketch).

81. *Are they treated, and if so, how?*

Pins are treated in the following ways:

1. Boiled in paraffin about 24 hours.
2. Boiled in linseed oil about two hours.
3. Painted.
4. Dipped in elastic bitumen.

In a great many cases pins were not treated in any way.

In all cases where wood pins were used they were boiled in paraffin for 24 hours.

83. *Are the pins fastened in the cross-arm and pole, and if so, how?*

Pins are fastened to cross-arms in the following ways:

1. Nailed (in most cases).
2. Nut and washer (when iron pins are used).
3. Wooden dowel (in one case).
4. Iron spring (in one case).
5. Driven into cross-arm tightly.

The following methods are used to hold pins in cross-arms and poles:

1. Pins screwed into top of pole.
2. Nut and washer (iron pins).
3. Nailed through cross-arm.
4. ½ in. and ¾ in. oak dowel.

82. *What are the dimensions of the pin?* (*A sketch is desirable.*)

See sketches showing various size pins, Figs. 16-21

VII. TELEPHONE LINE.

85. *Have you telephone lines upon your transmission poles?*

All plants with the exception of four have telephone lines on same poles as the power lines. One plant in Class F has its telephone line on separate poles 200 feet from the power line.

87. *What kind of pins, insulators, and cross-arms or brackets are used?*

Majority of plants use standard side brackets, cross-arms, pins, and glass telephone insulators.

Fig. 16

27000 Volt Pin

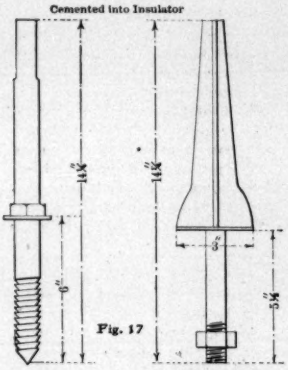
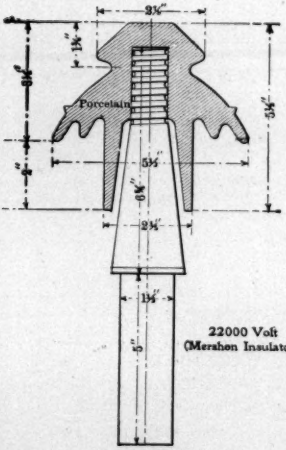


Fig. 17

Top Pin Cross Arm Pin

30000 Volt Iron Pin



22000 Volt
(Merahon Insulator)

FIG. 19

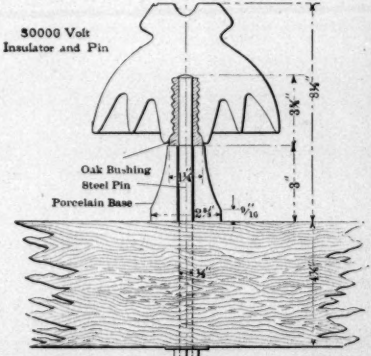


FIG. 20

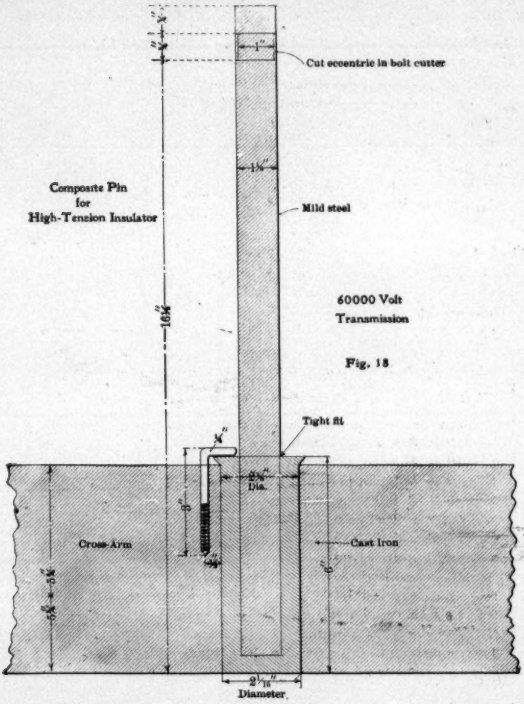

Cut eccentric in bolt cutter
Composite Pin for High-Tension Insulator
Mild steel
60000 Volt Transmission
Tight fit
Cross-Arm
Cast Iron
Diameter

Fig. 18

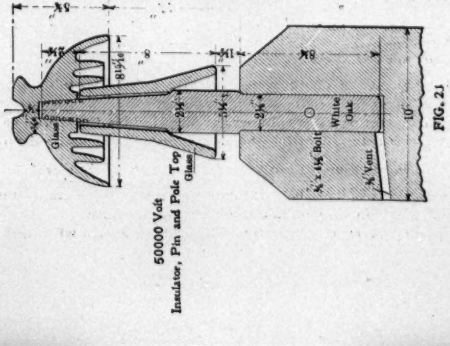

Glass
Top Glass
White Oak
Bolt
Vent
50000 Volt Insulator, Pin and Pole

FIG. 21

86. *How often are they transposed, and at what intervals of distance?*

The following are methods of transposing telephone lines:

Classes A, B, C, D.

Every 5 poles (approximately 500 feet).
Every 10 poles (approximately 1000 feet).
Every 4 poles.
Between every pole.

Classes E, F.

Every 2 poles.
Every 3 poles.
Every 1600 feet.

88. *Are the pins, cross-arms, or brackets treated? If so, how?*

Pins, brackets, and cross-arms are treated in the following ways:

Painted.
Paraffined.
Creosoted.
Linseed oil.
About one-half the plants do not treat pins, brackets, etc.

89. *What kind of conductor is used, and what size?*

The following are the kinds and sizes of telephone conductors:

No. 10 B. & S. copper hard drawn.
No. 10 B. & S. copper medium drawn.
No. 12 B. & S. copper hard drawn.
No. 10 B. & S. copper waterproof.
No. 6 galvanized iron.
No. 8 galvanized iron.
No. 9 galvanized iron.
No. 10 galvanized iron.
No. 12 galvanized iron.
No. 12 galvanized steel.
No. 10 B. & S. aluminum.
The majority of plants use No. 10 galvanized-iron wire.

90. *Is the circuit an all metallic one?*

All telephone circuits are metallic.

91. *Do you have stations for tapping on to your telephone line or do your inspectors attach their portable telephone to the line wherever they may happen to be?*

In the majority of plants inspectors attach their portable telephones to the line wherever they may happen to be.

In one case stationary telephones are placed in booths every two miles.

In three cases stationary telephones are placed in boxes on the poles.

92. *If so, what precautions are taken for the safety of the users?*

The majority of plants have insulated platforms for users to stand on, these platforms standing on line insulators in most cases.

One plant makes its inspectors wear rubber gloves when using telephone

93. *What is the normal distance between the nearest power wires and the telephone wires?*

The following are the maximum and minimum distances of telephone line from power lines:

Class A	B	C	D	E	F
2 ft. to 15 ft.	4 ft. to 10 ft.	4 ft. to 10 ft.	3 ft. to 6 ft.	4 ft. to 8 ft.	5 ft. to 8 ft.

96. *What means have you for the protection of the telephones, and those using them, from lightning and crosses with the power wires?*

The following means are used for protecting telephones and those using them from lightning and crosses with the power wires:

1. Lightning-arresters (in most cases).
2. Fuses to ground.
3. Film cut-outs.
4. Barbed wire.
5. Rubber hose on receiver cord.
6. Insulated stools or floors (in most cases).

97. *If you use telegraph instruments instead of telephone, state the reason why?*

One company (in Class F) uses a telegraph instrument for signaling. Two other plants use telegraph instruments, one of them only when telephone is not working.

98. *Show on sketch, position of telephone wires with reference to power wires, showing the normal distance apart of the telephone wires?*

See sketch showing position of telephone wires relative to power wires, pages 601-604

99. *What is the e.m.f., induced or other, between your telephone wires and the ground?*

Classes A, B, C, D.

Highest e.m.f. recorded between telephone wire and ground is from 20 to 130 volts.

Classes E, F.

In these classes highest e.m.f. was 3000 volts. A great many plants claim there is no e.m.f. between telephone wires and ground, due to: careful transposing; using good insulators and careful wiring; a reactive coil in line with middle point grounded.

VIII. TRANSFORMERS.

101. *What is the capacity of your transformer units in the power-house and sub-stations?*

Class A.

Transformer units at power-house range from 125 to 225 kw.; at sub-station from 7.5 to 375 kw.

Class B.

Transformer units at power-house range from 150 to 500 kw.; at sub-station from 75 to 300 kw.

Class C.

Transformer units at power-house range from 175 to 1400 kw.; at sub-station from 20 to 2250 kw.

Class D.

Transformer units at power-house range from 225 to 500 kw.; at sub-station from 125 to 350 kw.

Class E.

Transformer units at power-house range from 289 kw.; at sub-station from 150 to 500 kw.

Class F.

Transformer units at power-house range from 1000 kw.; at sub-station from 333 to 1000 kw.

102. *Are the transformers connected in* △ *or Y?*

The following are the various methods of connecting transformers:

1. △ (used in most cases).
2. Y.
3. △ and Y.
4. Scott or T, two-phase to three-phase (used in a great many plants).
5. Single phase.

103. *Is the same connection used on both primary and secondary sides?*

In the majority of plants the same transformer connections are used on both primary and secondary sides.

104. *Is the neutral grounded upon either the high- or low-voltage side? If so, why? If not, why not?*

In the majority of plants the neutral is not grounded at all.

105. *Do you know any marked advantages or disadvantages in grounding the neutral? If so, state them.*

The advantages of grounding neutral are:

1. To prevent high-tension from doing damage to low-tension network, should insulation between primary and secondary break down.
2. Reduces strain on transformer and line under normal conditions.
3. Prevents accumulation.

In one plant neutral is grounded on high-tension side. The reasons for it: less expense in transformer construction; greater safety in insulation of windings; greater flexibility of general system in case of loss of transformers, or one wire of the circuit, or anything which cripples any one part of the three which go to make up the system, we can still operate on two until we can change to the other line and repair it, and have no interference with service. Greater simplicity in wiring of stations; less interference with telephone wires and outside circuits, and we believe, less opportunity for resonance and other serious line effects. At least, we have never had any of these effects.

Disadvantages are:

1. Increases danger of accident to apparatus.
2. Double-current generator is short circuited if neutral of secondary is grounded.
3. Liable to damage telephone system if power line should become grounded or open.
4. Increases liability to side flash from lightning

106. *Is there a spark-gap connection to earth from the centres of either the high- or the low-voltage coils?*

About two-thirds of the plants do not have spark-gap connections to earth from the centre of either the high- or the low-tension coils.

107. *Have the transformers ground-shields between the high- and low-tension windings?*

Only three plants have ground-shields between the high- and low-tension windings of their transformers, but majority of plants have their transformer cases grounded thoroughly.

108. *Are the transformers oil-insulated or dry?*
109. *Are they air-blast, water-cooled, or natural-cooled?*
110. *What is the voltage of the low-tension side?*

TABLE D.

Class	Oil-insulated natural-cooled	Oil-insulated water-cooled	Oil-insulated air-blast cooled	Dry air-blast cooled	Range of voltage on low-tension side.
A	11	3	1	5	360 to 2300
B	4	2	1	0	350 to 2400
C	6	2	1	1	390 to 2400
D	1	3	0	2	2200 to 2300
E	2	1	0	2	750 to 2400
F	1	4	0	0	1500 to 4000

111. *Is there transformation of phase as well as of voltage?*

Only about 6% of the plants transform the phase of the current.

112. *Have you had any trouble with your transformers? If so, what?*

The following troubles with transformers have been experienced:

1. Terminals improperly soldered.
2. Transformer burnt out; cause, not dried out enough before being put into service.
3. Breakdown between primary and secondary coils, bad insulation being the cause.
4. Breakdown from lack of proper circulating ducts between coils and from canvas hoods over ends of coils, making dead places for oil; oil would heat and burn.
5. Burnout from lightning discharges.
6. Burnout from overloading.
7. Burnout from defective leads.
8. In one plant six natural-cooled, oil-filled transformers furnished with the first contact were failures; had to be re-

designed; since, have been all right. Thirty air-blast transformers have never caused one dollar for repairs in five years—with one exception, which was due to an attendant not noticing that a terminal had become unsoldered where two banks were operating in parallel, and its mate burned out after carrying overload of 100% for at least 15 days.

IX. LIGHTNING PROTECTION.

113. *What devices are used to protect your power lines from lightning? Lightning-arresters, grounded wires, or both?*

With the exception of one plant which uses barbed wire, lightning-arresters are used; four plants use both lightning-arresters and ground-wire.

115. *Are the wires smooth or barbed and of what material?*
117. *How are they fastened to poles or cross-arms; on insulators? If on insulators, why?*

Barbed wire is generally used in preference to smooth wire. Some plants run taps to ground at every pole, some at only every four poles, and some at only every half mile. For mechanical reasons this ground-wire is generally run on insulators; but in some cases it is fastened to pole or cross-arms with staples.

118. *How is the ground made?*

The following are various methods of grounding this ground wire:

1. Twisting around butt of pole.
2. Gas-pipe driven into ground 6 ft. to 10 ft., the wire put into pipe and pipe filled with about 4 in. of lead.
3. Galvanized-iron plates placed in ground.

119. *Do you consider grounded wires as a valuable protection?*
120. *Do you consider them more or less desirable than any other means of lightning protection?*

Only nine companies consider grounded wires a valuable protection; as a rule they are thought less desirable than other lightning protection.

121. *If lightning-arresters are used, do you consider that they furnish any protection against rise of voltage, due to any disturbance upon the system, such as the throwing on or off of all or part of the load, etc.*

The majority of plants consider lightning-arresters furnish protection against rise of voltage due to any disturbance upon the system such as the throwing on or off of all or part of the load, but a number of plants think that for a moderate rise of voltage they furnish no protection.

122. *Do you consider them a complete protection against such rise?*

The majority of plants do not think lightning-arresters are a complete protection against such rises.

123. *What kind of lightning-arresters are used?*

The following makes of lightning-arresters are used (in order of the quantity):

General Elec. Co. (Wirts).
Westinghouse Elec. Mfg. Co. (low equivalent).
Stanley Mfg. Co.

124. *Do you have banks of lightning-arresters along your line? If so, at what intervals?*

Lightning-arresters are placed in the following ways along the line:

1. At power-house and sub-stations only.
2. At each end and middle point of line.
3. At points dividing line into four equal parts.
4. At irregular intervals (at cable terminals, etc.).

125. *Are they necessarily at sub-stations?*

The greater number of plants consider it necessary to have lightning-arresters at sub-stations.

127. *Is there resistance in series or in parallel with the arresters? If so, what kind of resistance (such as carbon, metal, water, etc.)?*

Lightning-arresters have the following kind of resistances in series or parallel, or both:

Carbon resistance in series.
Graphite rods in series.
German silver in series.
German silver in series and parallel.

128. *Is there capacity or inductance in series or in parallel, with the arresters or line?*

Majority of plants have choke-coils in series with line.

129. *Do you find that the lightning-arresters do their work satisfactorily? If not, wherein do they fail?*

Majority of plants consider that lightning-arresters do their work satisfactorily, but some plants experience the following troubles:

1. Generator current follows a discharge to ground.
2. Lightning jumps to water coil on transformers.
3. Arrester put out of order after each discharge.
4. When switching high-tension circuits, generator current follows discharge to ground.

130. *How are the grounds made for your lightning-arresters?*

The following methods are used for grounding lightning-arresters:

1. Copper plate about 30 in. sq. placed below water level in river bank; two strands of No. 4 copper wire attached to different points of plate by solder, plate is then covered with about 12 in. of coke or fine charcoal and then rest of hole filled with damp earth. In some cases plate is kept wet by means of a water-pipe.
2. Galvanized-iron pipe driven into ground about 18 feet.
3. Coils of copper wire buried in bank of river below water line.
4. Connected to steel flumes, steel structure, or feed-water pipe.
5. Connected to rails in cases of electric railway.
6. Connected to negative bus-bars.

X. CABLES.

131. *Have you any cables included in your transmission line?*

Only eight plants have cables in their transmission lines.

133. *Are they lead covered?*
136. *Do you prefer rubber or paper insulation, and why?*

All cables used are lead-covered. One plant in Class A has a three-phase submarine cable 4300 feet long, steel armored.

In most cases where cables have been installed recently paper insulation is used; the advantages claimed for paper-insulated cables are:

Cheaper and more durable: rubber insulation deteriorates in short time. One plant claims that there is less trouble from moisture with rubber.

137. *Give sketch of section of cable, showing arrangement and size of conductors and arrangement and thickness of insulation and sheath?*

(Sketches of various cables used are shown, see Figs. 22-25.)

138. *Are the conductors solid or stranded?*

Stranded cable is used almost entirely.

139. *Is the sheath lead? or lead and tin? and is it iron armored?*
140. *If lead and tin, what is the percentage of the latter?*

Cables in most cases are covered with a composition of lead and 3% of tin—the tin lessens corrosion.

143. *What means do you employ to protect cable sheaths from electrolysis?*

The cable sheaths are grounded to rails, gas-pipes, etc. as a protection against electrolysis.

144. *What protective devices have you for the cables, and do they prove effective and satisfactory?*

The majority of plants have lightning-arresters as a protection for their cables, also overload circuit-breakers in stations.

145. *Do you take any unusual precautions in operating to ensure the safety of your transmission cables?*

In most cases no unusual precautions are employed in operating to ensure the safety of transmission cables.

146. *What kinds of ducts do you employ for carrying your cables?*

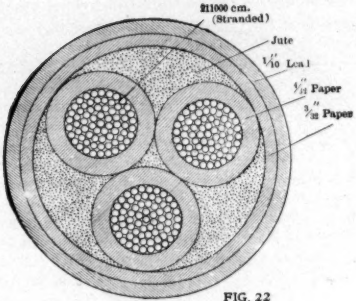
The following are different kinds of ducts used for carrying cables:

Vitrified clay.
Cement-lined vitrified clay.
Creosoted wooden boxes.
Iron pipes (when cables run under water)

XI. OPERATION.

147. *Do you do your switching on the high- or the low-tension side of the transformers?*
148. *If the former, do you switch circuits when there is voltage on them but no current?*
149. *Do you switch high-tension circuits when loaded?*

Sixty-five per cent. of the plants do their switching both on low- and high-tension sides. In classes A and B in a great many plants switching is done on low-tension side only. In Class A, 50% of the plants do their switching on high-tension side only. The majority of plants make it a practice to switch their high-tension circuit with volt-



4600 Volts

FIG. 22

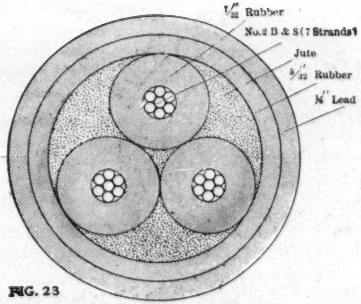


FIG. 23

25000 Volts

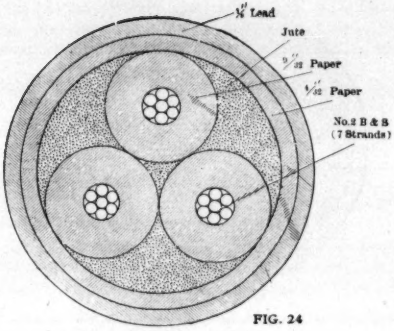


FIG. 24

25000 Volts

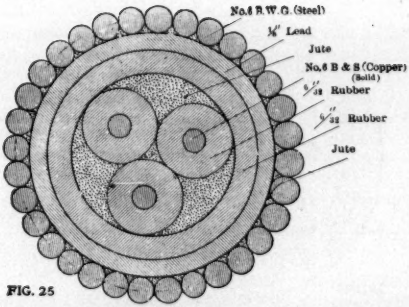


FIG. 25

12000 Volts Submarine

age on them, but no current. A number of plants, probably 40%, switch their high-tension circuits when loaded, and about 10% will do it only when it is absolutely necessary.

150. *What means for high-tension switching do you have?*

Following are the high-tension switches used in order of the quantity in use:

Oil-switches.
Fused-switches.
Air-switches.
Knife-switches (quick break).

Ram's horn: the horn is of ½-in. brass rod, curved and converging to a gap of about 10 in. In stations where there is any large amount of synchronous apparatus, this gap is spanned by a solid ½-in. rod set into suitable clips on the horns and provided with a suitable operating handle. In simple transformer stations the gap is spanned by a 1-in. porcelain rod having brass contact-pieces with binding screws for ordinary fuse-wire. These switches have been operated successfully on loads as large as 3000 kw.

151. *Is it satisfactory? If not, why?*

All plants claim their way of switching is satisfactory.

152. *Do yon have high-tension fuses, and if so, what type?*

The following kinds of high-tension fuses are in use:

Ball type.
Pole type.
Expulsion fuse.
D. & W. powder fuse.
Porcelain enclosed.
Glass enclosed.
Expulsion aluminum.
Sach's Noark.

154. *When you open a loaded high-tension main circuit with an air-break switch, do the lightning-arresters discharge?*

155. *If instead of an air-break switch an oil-break switch is used, does it have the same effect?*

In classes A, B, and C when loaded high-tension main circuits are opened with air-break switch, the lightning-arresters *do not* arc, but in classes D, E, and F they generally *do* discharge. But plants using oil-switches are not troubled to the same extent with their lightning-arresters discharging when they open a loaded high-tension main.

156. *Do you operate with grounded neutral? If so, why? If not, why not?*

A very small percentage of the plants operate with neutrals grounded.

157. *Have you ever had any trouble due to operating with grounded neutral either in your power circuits or because of trouble with neighboring power, telephone, or telegraph circuits?*

Yes; a number of plants operating with grounded neutrals affected telephone and telegraph circuits in the neighborhood. One company says if all the power of one of the large power stations be transmitted over

the whole length of the circuit with one wire of the transmission line open the telegraph companies are affected, but as this never occurred but for an instant once or twice it is not serious. We can still talk on our own telephone line with the sub-station carrying 500 kw., working with two transformers as above mentioned, and affect no neighboring power circuits, nor does it affect our own circuit on neighboring poles when running separate.

158. *Have you ever had one power-wire broken or one leg of the circuit open under a heavy load when the neutral was grounded?*
159. *Did this cause damage or trouble in any of your circuits or in other circuits, near or remote? If so, what?*

A few plants have had one power-wire broken or one leg of circuit open under a heavy load when the neutral was grounded, but in most cases no damage was done.

160. *Have you ever had trouble from the burning or charring of pins, cross-arms or poles due to the high-tension current?*
166. *What means have you taken to remedy the trouble and have the means proved effective?*

A great many plants have had trouble with burning of pins, cross-arms, or poles. In most cases this was due to continuous discharges, caused by:

1. Pin or insulator breaking; generally remedied by replacing pin or insulator.
2. Spray from falls freezing on insulator; remedied by moving line farther from falls discharging across insulator.
3. Bad insulator starting leaking to ground wire; remedied by moving ground wire from face of cross-arm.
4. Insulator with iron pin cracking and burning arm.
5. Pins burn, due to rain; remedied by replacing porcelain insulator with glass. In some cases discharge appeared to come from inner petticoat, in others through the porcelain and burning pin ½ in. from top.
6. Poor porcelain; remedied by replacing untreated oak pins with locust pins that have been boiled in paraffin and painted with P. & B. paint; also painted thread of insulator.
7. Gases from quartz mill forming film over surface of insulator.
8. Soot from passing trains being deposited on insulators; remedied by cleaning insulators and replacing pins.

In most cases discharge was worse in wet and foggy weather, and in many cases discharge took place in wet weather only.

167. *Have you had any trouble from insulators puncturing or current flashing around them?*

Only about 6% of the plants have had trouble from insulators puncturing or current flashing round.

168. *If the latter, what was the cause?*

The cause being either insulators damaged by stones or defective porcelain or glass, more often the latter.

169. *Do you have many insulators maliciously broken?*
170. *If so, what means have you taken to stop this, and with what success?*

A great many plants experience trouble from having their line insu-

lators maliciously broken. The following means have been taken to stop this:

1. By posting warnings.
2. Offering rewards for evidence that will enable them to locate and convict guilty persons.
3. Having watchmen along line.
4. Arrest and fining.

(Not much success with any of above methods.)

171. *Have you had any insulators break from internal strains when on the line?*
172. *Was this from actual strains in the glass or from improper placing upon the pin?*

Only a few plants have had insulators break from internal strains when on the line, the cause in most cases being the improper placing of insulator on pins.

173. *Have you ever had arcs start between your line wires?*
175. *Are you troubled from short circuits upon your lines? If so, what are the most serious causes?*

The following are causes for arcs being started between lines:

1. A piece of wire maliciously thrown across lines.
2. Branches of trees falling across lines.
3. High winds blowing wires together.
4. Large birds coming in contact with lines.
5. Broken insulators and pins.
6. Sleet storms.
7. Lightning discharges.
8. Generators ran away, due to sudden change in load.
9. Fields of generators demagnetized owing to armature reaction.

176. *Is your telephone system satisfactory?*
178. *Is there much more noise with a heavy current in the power-line than with a light current?*

Most plants claim that their telephones work satisfactorily; but a great number of plants complain that their telephones are more or less noisy in wet weather. One or two plants claim that telephones work better in wet weather, one of these plants belong to Class F.

Majority of plants claim that the amount of current in power-line does not affect their telephones. One plant says the heavier the load the less the noise in the telephones.

179. *Have you ever had any one hurt from the power voltage when using the telephone? If so, how did it happen?*

Only one accident recorded in connection with telephone; superintendent of power-house was killed at telephone. They think heavy sleet on power-wire made it sag until it touched telephone wire.

181. *Do you do work upon dead circuits when other circuits on the same pole-line are alive? If so, what precautions do you take?*
182. *Are such repairs made only in dry weather and in the daytime, or are they made at any time?*

Majority of plants do work upon dead circuits when other circuits on the same pole-line are live; the following precautions are taken:

1. Ground dead circuits.

2. Short circuit dead circuits.
3. Both ground and short circuit dead circuits.

In classes A and B where circuits are close together on cross-arms all circuits on same side of pole as dead circuit are made dead.

Majority of plants repair their lines at any time, day or night.

183. *How do you have your circuits patrolled and how often?*
184. *How much distance is one man able to patrol satisfactorily and over what kind of country?*

Lines are patrolled at different intervals of time ranging from once a day to five or six times a year, according to the kind of country passed through. Lines running by railway are often patrolled by men on a hand-car, lines cross-country by men on foot and on horseback. The amount of line that a man can patrol in one day varies with the kind of country: on level country ten miles; on hilly country from three to six miles. A man on horseback can do about 30 miles on level or about eight miles in mountainous country.

One company has a lineman and helper to look after 30 miles of line; they patrol line twice a week.

Another company has three men on hand-car who patrol 30 miles a day.

A number of plants do not have their lines patrolled regularly, but only when trouble occurs.

185. *What means are taken to compensate for capacity charging current of transmission lines?*

No special means are taken to compensate for capacity charging current of transmission lines by plants.

186. *Is voltage drop compensated for at receiving stations? If so, how?*
187. *Where there is more than one receiving station, what means, if any, are used for independently regulating the voltage desired by these stations?*

The various methods are used for compensating voltage drop at receiving stations:

A number of taps on transformers.
Regulators on secondary side of transformers.
Regulating heads on transformers.
Motor-driven potential regulators
Synchronous converters over-compounded.
Synchronous motors.

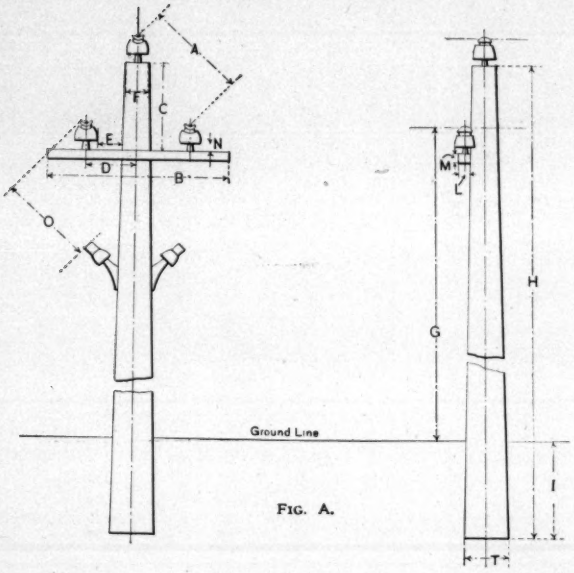


FIG. A.

Voltage.	A	B	C	D	E	F	G
16 000	18″	24″	16″	9″	—	6″	—
22 000	30″	68″	24″	15″	—	—	27′
22 000	30″	42″	26″	15″	8″	7″	15′
27 000	48″	64″	42″	24″	11″	12″	35′
30 000	40″	60″	23″	20″	12″	7″	22′2″
40 000	108″	120″	84″	54″	43½″	7″	19′6″
50 000	60″	72″	52″	30″	20½″	7″	26′6″
50 000	78″	96″	67½″	39″	29″	10″	23′6″
45 000	42″	50″	36½″	21″	10″	8″	27′8″

Voltage.	H	I	J	K	L	M	N	O
16 000	30′	5′	10″	—	4″	5″	2½″	48″
22 000	35′	6′	—	—	4″	4″	3″	120″
22 000	25′	4′	—	—	3½″	4½″	—	60″
27 000	45′	7′	17″	—	6″	6″	—	72″
30 000	22′3″	6′	—	—	3½″	4½″	—	72″
40 000	35′	5′6″	16″	—	5½″	3½″	10″	—
50 000	35′	5′6″	—	—	4½″	4½″	2½″	60″
50 000	35′	6′	14″	—	3½″	5½″	1½″	72″
45 000	35′	5′6″	12″	—	5½″	5½″	2½″	96″

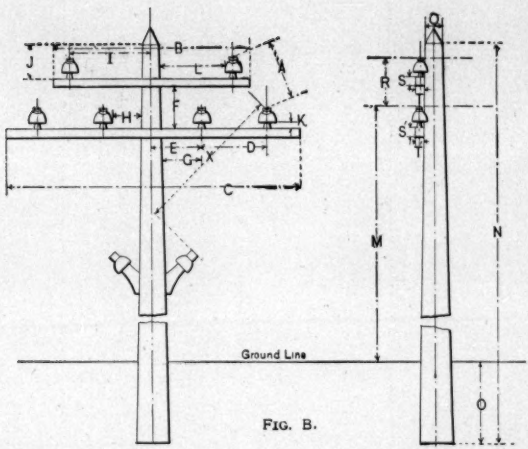
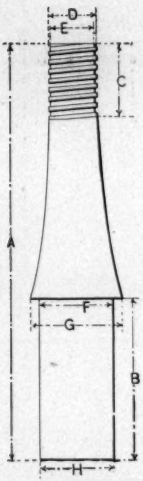


FIG. B.

Voltage.	A	B	C	D	E	F	G	H	I	J	K
12 000	24″	54″	72″	18″	14″	17½″	—	8″	23″	—	3″
11 000	20″	54″	72″	20″	12″	16″	8″	8″	22″	8″	4″
11 500	24″	60″	84″	24″	12″	20½″	9″	9″	24″	5″	2″
23 000	30″	72″	102″	30″	15″	26¼″	—	8″	30″	8″	2½″
25 000	18″	60″	86″	24″	—	—	—	8″	22″	—	—
34 000	25½	62″	80″	18″	18″	20″	14″	—	27″	8″	3
30 000	30″	78″	108″	30″	18″	22″	9″	6″	33″	8″	4″

Voltage.	L	M	N	O	P	Q	R	S	T	S'	T'	X
12 000	17″	21′	30′	6′	—	—	22″	4½″	3½″	4½	3½	72″
11 000	—	—	35′	5′	18″	7″	—	4″	5″	4	5	96″
11 500	18″	—	24′	4′	—	6″	20½″	4½″	3½″	4½	3½	—
23 000	23″	23′	30′	5′	12″	7″	—	4½″	3½″	4½	3½	48″
25 000	—	30′	36′	6′	14″	7″	—	5″	4″	5	4	72″
34 000	19½″	—	35′	5′	12″	8″	24″	3½″	2½″	4½	3½	66″
30 000	24″	27′	36′	6′	16″	10″	26″	5″	4″	5	4	48″



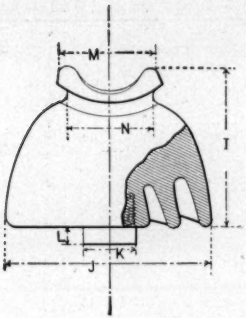


FIG. C.

Voltage.	A	B	C	D	E	F	G
12 000	11″	4½″	2″	1″	½″	1½″	2″
4 600	9″	4″	2″	1″	⅜″	1½″	1¾″
11 500	8½″	4″	2½″	1″	13/16″	1 7/16″	1 11/16
12 000	9″	4″	2″	1″	½″	1½″	2½″
16 000	10½″	4½″	2″	1″	⅜″	1½″	1½″
20 000	10″	4½″	2½″	1″	⅜″	1½″	1½″
25 000	12″	4″	2½″	1¼″	⅜″	1½″	—
30 000	10″	4½″	2½″	1″	½″	1 9/16″	2″
50 000	18½″	4½″	3½″	1″	13/16″	2 7/16″	2 15/16″

Voltage.	H	I	J	K	L	M	N
12 000	1½	4″	5″	2½″	½″	2½″	2½″
4 600	1½	—	—	—	—	—	—
11 500	1½	4½″	5½″	2″	—	3½″	2 3/16″
12 000	1½	4½″	6″	1 5/16	3/16″	2½″	3″
16 000	1 15/32	4½″	6″	—	—	3″	—
20 000	1½	4″	5½″	2½″	1½″	2½″	2½″
25 000	1½	—	—	—	—	—	—
30 000	1½	5″	7″	2½″	—	3½″	2½″
50 000	2 7/16	9″	10″	4½″	3½″	4½″	3½″

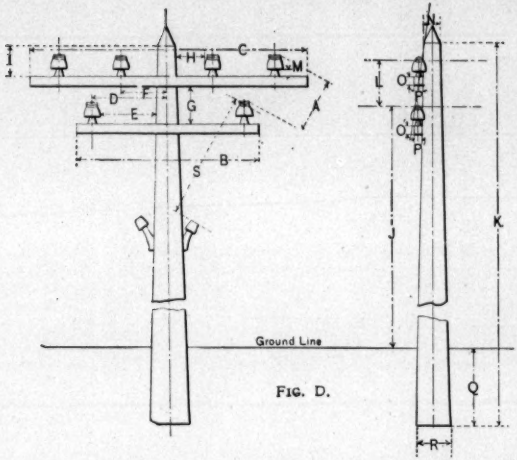


FIG. D.

Voltage.	A	B	C	D	E	F	G	H	I	J
12 000	24″	84″	84″	24″	17″	12″	16½″	5″	4″	32′
12 000	30″	72″	96″	29″	—	14″	21″	—	—	22′
15 000	30″	61″	96″	26½″	—	9″	27″	—	6″	32′
22 000	30″	68″	99″	—	30″	15″	24″	15″	9″	27′
24 000	36″	96″	132″	36″	—	18″	25½″	—	24″	25′

Voltage.	K	L	M	N	O	P	O′	P′	Q	R	S
12 000	39′8″	21″	3″	8″	4½″	3½″	4½	3½	6′	16″	54″
12 000	30′	26″	—	6″	4½″	4½″	4½	4½	5′	—	—
15 000	40′	31½″	—	7″	4½″	3½″	4½	3½	6′	16″	10′
22 000	35′	30″	—	6″	4″	4″	4	4	6′	—	120″
24 000	35′	31½″	—	8″	5½″	5½″	5½	5½	6′	14″	30″

For the Committee on High-Tension Transmission.

RALPH D. MERSHON,
Chairman.

DISCUSSION ON HIGH-TENSION TRANSMISSION REPORT.

J. H. FINNEY: Is not the spacing between wires given in Class E, in error? In the other classes the spacing seems to increase in direct ratio, but in Class E, for 31 300 volts, the spacing is only 31 inches. Is not this a mistake?

RALPH D. MERSHON: The figures were examined carefully so as to prevent mistakes. There are not very many plants in this class, only four; so it depended on the choice of only four men to decide the average.

PETER JUNKERSFELD: Answer 5, Class A, on page 576 of the Committee's Report refers to the use of a ground-net of 0.25 inch steel cable suspended across the right of way and under power wires. This is of interest as it has been proposed by the Underwriters for insertion in the National Electric Code. It would be interesting to know the extent to which such ground-nets have been used and what degree of protection can safely be credited to them.

PRESIDENT ARNOLD: These nets are installed under high-pressure transmission lines in a number of places between Chicago and New York on lines parallelling the Lake Shore and the New York Central railroads, also between Chicago and Denver. They are in much more common use in Europe. We have just begun to use them; as a particular instance they may be found on the line of the Fonda, Johnstown, & Gloversville Railway.

L. SCHULER: Ground-nets are used in Europe to a great extent, especially in Germany and Switzerland, as the authorities require them for a high-pressure line crossing a highway. It has been found, however, by experiment that in nearly all cases the wire, if broken, will, in consequence of its twist, jump over the side of the net. If a high-pressure line crosses a railroad, the authorities usually require a completely closed tunnel of iron work through which the line passes.

RALPH D. MERSHON: The speaker has put in one or two of these ground-nets himself, but he does not think very much of them. They are generally put up as a matter of sentiment, as a protection in the event of lines coming down, especially from sleet. If it is feared that the lines will come down from sleet, then of course the netting has to be strong enough to carry any sleet that might collect on it. A netting could be put in strong enough to take care of any probable load of ice or snow, but that would mean a rather formidable sort of structure. Probably the best method of protecting lines liable to be crossed by high-pressure wires is, if possible, to put the poles of the crossing line on each side of the line crossed; have these poles close together, and so high that if the upper line breaks it cannot possibly reach the line crossed. Such construction is as near absolute protection to the lower line as you can get against anything short of the main line falling down sideways.

S. B. STORER: The Utica and Mohawk Valley Railroad Company have a short section of their line fitted with the netting underneath. This netting is made of two iron wires on either side of the cross-arm; these wires are twisted and at intervals of about six feet there are three-cornered sticks from one side to the other that are expected to hold the transmission line in case it breaks. The iron wires supporting these sticks are mounted on insulators of exactly the same type as used on the transmission line, so that even if one of the two transmission wires should break there is no tendency for it to ground. The speaker does not like this kind of construction, because he thinks the netting or cradle suspension should be permanently grounded. An iron cross-piece is preferable to a wooden cross-piece for the reason that in using synchronous motors or synchronous converters, one line might break and the two ends drop on this netting, and the machines would go on operating just as they were before. If this did happen, and the wooden cross-pieces were wet, they would carry the current to the iron span-wire thus completing the circuit through the cross-pieces and the iron wire. This would quickly burn the cross-pieces and the wires would drop down just the same as if no support were there. Perhaps it would be much better to have a strong iron netting underneath the transmission line and have the wires of such capacity as to carry a short circuit without burning off.

F. A. C. PERRINE: At the National Electric Code meeting last year this subject was carefully discussed. The Underwriters were at first very strongly in favor of a netting, but the question just asked by Mr. Storer, whether the netting should or should not be grounded in any case, came up at once. It seems important that the netting should have at least as great carrying capacity as the transmission wire itself, otherwise the netting would burn off by reason of the wire grounding.

The second plan proposed by the Underwriters was the one mentioned by Mr. Mershon, that of setting the poles close enough together and elevating them to such a height that a break in the wire could not bring the transmission line in contact with any wire crossing underneath it.

There were, if the speaker remembers correctly, three methods accepted by the Underwriters: first, guard wires placed on the ends of the cross-arm carrying the telephone wires and above them so that the transmission line could not come in contact with the telephone line by breaking. This was the preferred method, and it was left to the discretion of the transmission company whether it would ground or insulate the guard-wires, it being considered that it would make very little difference which was done. The grounding of it would have a tendency to burn off the transmission line, but in either case the transmission line could not come in contact with the telegraph

or telephone wires. The other two methods were admitted as permissive. In the second method the transmission line would have to be raised the height of the street above the telegraph and telephone lines, so that in case of a break it would fall out of contact, which means that in a 60-foot street the transmission line would have to be 60 feet above the telegraph and telephone lines. The third method was the use of a grounded screen. In that case the screen should have more carrying capacity than the transmission line itself, so that in no case would the screen be burned through. All of these systems were recognized as being deficient, but after discussion lasting one day in which the National Electric Light Association, the Pacific Coast Transmission Committee, the INSTITUTE, and the Underwriters were involved, that was the best that could be gotten out of it.

The importance of this is very great, for there has been at least one instance of a transmission line falling across a long-distance telephone line and burning out all the instruments within many miles, and burning down a house. But it is questionable whether these guard-wires are sufficient protection. The speaker thinks there is not yet any very well-established experience.

EUGENE CLARK: Dr. Perrine has not mentioned one serious fault of any form of netting: the transmission span would generally be from 100 to 300 feet long at a crossing, and the netting under the line would necessarily be only a few feet wide. Under such conditions, a broken transmission line would probably curl up and fall off from the netting. Under such conditions, the netting would be useless unless thoroughly grounded.

S. B. STORER: The speaker understands that in Switzerland they make use of a ring projecting from the cross-arm through which each transmission wire passes; these rings are on both sides of the insulator so that if the wire breaks it will strike the ring before the ends touch the ground. These rings are grounded. Has any one here seen that construction, and does it afford protection?

W. B. JACKSON: It is used upon the Valtellina Road in Italy, where the high-pressure wires are equipped in this manner at each road crossing. Although the rings operate very satisfactorily in case of a break in the line, they sometimes give trouble when the lines do not break, and the engineers consequently found it desirable to have them cut out.

PRESIDENT ARNOLD: Why should the ring operate without the wire breaking?

W. B. JACKSON: They found that to give a sure grounding when the line broke they had to make the ring quite small or had to carry it a considerable distance out from the cross-arm, otherwise the wire might drop and not ground; but if they got it too small or too great a distance from the cross-arm there was danger of its becoming slightly displaced and thus causing a ground when such was not desired.

N. J. NEALL: On page 594, rubber insulation is said to deteriorate in a short time. What is the relative depreciation in rubber cable?

JAMES LYMAN: Several cases have come to the speaker's notice of lead-covered, rubber-insulated, single-conductor cable, used for station wiring, where the rubber has deteriorated very rapidly, and broken down after only a few months' service. It is probable that in these cases a high static pressure was induced. The rubber seemed to be cut, and acted upon as if ozone had been present. In one case the cable was used on 13 200 volts pressure, 25 cycles; it was made to stand a working pressure of 30 000 volts, and breakdown pressure of 50 000 volts. After operation of about two months it went to pieces at different times, under normal operating conditions. There was no question regarding the good quality of the rubber insulation. There were six of eight different breakdowns at different times, thus indicating that they were not due to any defect in the cable itself. Another case came to the speaker's knowledge of a single, lead-covered, rubber-insulated cable, used on 13 200-volt, 60-cycle current, good for perhaps 20 000 volts—that broke down in the same way. For these reasons the speaker does not recommend the use of single-conductor, lead-covered cable, either on 25- or 60-cycle work, for station or outside wiring, where the pressure is above 5000 or 6000 volts; below that there is not much danger of the static dischage. The speaker knows of a number of cases where single-conductor, lead-covered cable is used on 6000 volts, and no trouble has been experienced.

GENERAL DISCUSSION ON HIGH-TENSION TRANSMISSION MATTERS.

W. G. CARLTON: Regarding the comparative reliability of overhead and underground lines, President Arnold and Mr. Wirt have both pronounced in favor of the overhead line. The speaker would like to hear something of the conditions under which President Arnold was considering this question; it seems that there are not very many cases where overhead lines can be the more reliable.

PRESIDENT ARNOLD: Of course it is not advisable to make a general statement that the overhead line is the more reliable and is always the line to install, because it is well known that in city work the use of underground or conduit is practically compulsory; in these circumstances it is unquestionably the more reliable because it is not subject to malicious interference, at least not to any such extent as an overhead line might be. When considering transmission lines, extending across country or through a region more or less settled—especially on private right of way—the speaker's conclusions are the same as those of his associates, that the overhead construction is preferable. It is preferable for two reasons: first, much less in first cost, and presumably in maintenance; secondly, it is much more accessible to repair in case of accident, because the trouble may be easily located and quickly repaired. These advantages do not obtain in the case of underground or conduit work. Any one that is installing electrical plants will admit that it is cheaper to construct overhead lines, and where these lines are permitted they are usually installed.

CHARLES F. SCOTT: President Arnold has said that underground wires are considerably more expensive to install than overhead wires. About what per cent. of the plant investment is represented by the transmission construction?

PRESIDENT ARNOLD:—Our case is one which would make the underground construction cost more in proportion to the overhead than in ordinary cases, for the reason that there are so few wires to carry, the maximum number being six and part of the way only three wires. In building this line we are running through rock almost all the way and will have to blast a large part of it. It is a case of digging and blasting a trench 57 miles long, so our preference for an overhead system is obvious.

PETER JUNKERSFELD: In replying to Mr. Scott's question, a comparison might be made with the high-pressure 25-cycle transmission systems in large cities, many of which represent from four to seven per cent. of the investment in the entire central station system. In the case in question the percentage would not be much higher, and probably is lower because of the heavy investment in car equipment, track construction, power-houses, and so on.

PRESIDENT ARNOLD: Perhaps it will be lower than that. The speaker cannot give an exact figure.

RALPH D. MERSHON: A plant with which the speaker has been associated has a transmission line of about 17 miles in length. The pressure at the terminal station is 22 500 volts. The last 3600 feet of this line consists of four three-phase cables each 3600 feet long. This line has been in operation for about three years. During that time, so far as the speaker knows, there has not been any trouble with the cable, except once when a defective joint was at fault, due to bad workmanship when the cable was installed. This cable is protected by choke-coils and lightning-arresters at the terminal house where the overhead line enters it; and although there are on this transmission system two grounded wires for protection against lightning, yet lightning occasionally comes across the arresters. Some short pieces of the cable are used for wiring at the generating station, and have at times a pressure of 25 000 volts. The neutral point is grounded at the generating station only. In this installation the cable-bells are made of hard rubber, with leads brought up through hard-rubber tubes, the bells being filled with paraffin.

N. J. NEALL: The allowance for depreciation of poles is, to-day, an important item in the fixed charges for a transmission line. It would therefore be interesting to know whether this statement as to life of various kinds of poles represents the depreciation as estimated by the various companies answering these questions, or the years they have used the different kinds of woods, or their opinion as to the relative values of different woods expressed in depreciation.

PRESIDENT ARNOLD: We can say offhand that very few maintain that a wooden pole will last for 15 years or even for 10 years. It is likely that the figures given in the report represent the life of a pole from a theoretical viewpoint. A pole may last for 10 or even for 15 years—subjected as it is to continuous attacks from the elements—but 15 years is assuredly the maximum limit.

RALPH D. MERSHON: In his Introduction Mr. Carlton barely touched upon the question of the possibility of high-frequency pressure effects due to an unconfined arc from a defective cable. Will Mr. Carlton please refer to this matter now?

W. G. CARLTON: Only one case of that kind has come to the speaker's attention. It happened in New York, and did considerable damage. In our experience in Chicago nothing of that kind has happened, but there is always a possibility of it happening.

CHARLES F. SCOTT: There is a station in New York, the Kingsbridge station, which has been operating for a year or two with open-air switches. It operates at 6600 volts, sometimes in parallel with the other power-houses.

W. G. CARLTON: This possibility of a rise in pressure in opening a high-pressure circuit in the air is generally conceded. A number of tests made here by Mr. Eastman have demonstrated it, and the results are decisive.

G. N. EASTMAN: The tests were made on a three-mile length of 2/0 three-conductor, paper-insulated, lead-covered cable with only the charging current of the cable. A static voltmeter was connected between one conductor of the cable and ground and an oil-switch and air-switch connected in series with the cable, so that they could be opened alternately. The oil-switch was so arranged that one break or a number of breaks in series could be made. The air-switch had but one break. By opening the air-switch very gradually, drawing out the arc, the rise in pressure was 40 to 50% above the normal. With the oil-switch no rise in pressure could be detected when the switch was opened having several breaks in series; with one break only a slight rise was detected when the switch was opened very slowly. These tests were duplicated, using the spark-gap instead of the static voltmeter, and the same indications were obtained. When the air-switch was opened, the charging current increased as the length of arc increased. By carefully drawing out the arc, a charging current seven times its original value could be obtained.

RALPH D. MERSHON: In his introduction Mr. Carlton seems to intimate that if a fire-proof cover were installed around a cable, thus confining the arc, there would be no oscillation; if the arc were not confined there probably would be oscillation. Has Mr. Carlton made any experiments that would justify this intimation?

G. N. EASTMAN: No; but the same conditions would prevail in the case of a short circuit as would obtain in the switch when opening under certain load conditions. From the results of experiments made by Dr. Steinmetz the speaker believes that he recommends the wrapping of cables in order to confine the arc.

RALPH D. MERSHON: Granting that a rupture of short circuit by oil might give very different results from an arc in air, it doesn't necessarily follow that you get in a confined arc the same results you would in oil. Has there been, so far as you know, any definite experiment tending to show pretty conclusively that cables protected in this way if they burn out are less likely to produce dangerous oscillatory effect than if they burn out in the air without this cover?

G. N. EASTMAN: So far as personal knowledge goes, no experiments have been made along this line, but the harmonic which is evidently obtained appears to depend upon the length of the arc. For instance, in all of the tests which were made in interrupting the charging current of the line, a certain length of arc would give a definite charging current, and an increase in the length of arc would give an increase in current.

H. B. ALVERSON: The speaker has witnessed tests of oil-switches with an ordinary steam-gauge put on the breaking chamber, the amounts of oil being varied from nothing up. In opening under oil the pressure varied from 50 lb. to 300 lb. depending on the point on the curve where it was broken, and an oscillograph in the circuit showed no pressure rise. With air only in the chamber, the air pressure would be from 10 lb. to 15 lb., while the oscillograph would give variations in which the pressure rise would go as high as twice normal pressure, the results being similar to opening arcs in air.

RALPH D. MERSHON: One would think that in a three-phase cable a short circuit would result in a definite length of arc determined by the distance between the conductors, and that there would not be much variation in the length of this arc. It seems to the speaker that unless definitive experiments are made with actual reference to the short-circuiting of cables—closed or open arcs—one could not draw satisfactory conclusions.

G. N. EASTMAN: We have had some short circuits happen between the conductor and ground, and the circuit-breaker at the station opened before the short-circuit had sufficient time to destroy the insulation between conductors. In one case where this occurred, the conductor on which the short-circuit was established was burned in two, but the insulation remained sufficiently high on the other two conductors of the cable to allow their being operated at the normal system pressure. This occurred on the 9000-volt system of the Chicago Edison Company in which the neutral was grounded, and the ground which occurred was a direct short circuit on one phase of the generators.

F. WOODMANSEE: The speaker was interested in making a test at Kalamazoo, a few years ago, to determine the effect on line due to the rupturing of the circuit by means of oil- and air-break switches. In that test it was found, in breaking a loaded circuit with an air-break switch, that surging occurred at instant of breaking the arc, but when rupturing the circuit by means of oil-switches there was practically no surging at all. These results were verified by spark-gaps connected across the line, as well as by means of an oscillograph.

The breaking of the circuit by means of allowing the arc to rise and break from what is known as a "goat-horn" was tried. On two occasions the light breeze extended the arc until it was about 33 feet long. At that instant it short circuited the load and reactance-coil, making a dead short-circuit on the system. On opening the switch there was a pressure rise on line of at least three or four times that of the operating pressure. This was verified by the spark-gaps. These tests demonstrated that the rupturing of high-pressure heavily-loaded or short circuits by means of air-break switches was dangerous, while they could be opened with safety by means of oil-switches without any very great rise in pressure.

RALPH D. MERSHON: Have any experiments been made with definite arc length? In opening an air-brake switch the practice is to start from zero arc and increase gradually until the maximum arc of this switch is reached; in doing this the length of arc may be struck that will give surprising results, results that might not be obtained with short arcs.

It seems to the speaker that Mr. Carlton's Introduction contains a timely reference to the very important subject of protecting cables from one another when one of them happens to fail. Now if the idea is simply to protect these cables from the heat of adjacent arcs it might be done by the scheme outlined by Mr. Carlton—the use of tile or brick—but if in addition we can, by asbestos wrapping, protect to a more or less extent against abnormally high pressure due to oscillatory effects, then it would seem that the protection by such wrapping were much to be preferred. Up to the present time, this discussion has failed to elicit any definite data as to the effects resulting from the burn-out of a cable,—the question naturally arises, will there necessarily be a higher pressure with the open air than with the enclosed arc?

F. WOODMANSEE: Regarding the first point raised by Mr. Mershon, an instrument was used to determine the length that the arc was drawn out. This instrument was used with both the air-break and oil-switches. The shorter the length of arc the less pronounced the surging effect.

W. G. CARLTON: Referring to Mr. Wirt's remarks, the asbestos wrapping would protect the cable from arcs due to adjoining cables; but in the case mentioned, the sheet-steel covering was used to confine the arc. If a high-pressure, three-conductor cable burns out and the circuit-breaker does not open the line, there will not be any cable or asbestos left where the arc is; in some cases three or four feet, or even more, of the cable has been entirely destroyed.

RALPH D. MERSHON: Of course if cables are laid on tile shelves and not wrapped or covered with the iron sheathes mentioned by Mr. Carlton, there would not be any confining of the arc. Now in order to avoid any dangerous effects from the arc—if the effects can be avoided by confining the arc—the arc would have to be confined in such a way as to develop a fair amount of pressure. If this were done, some precautions would have to be taken as to the strength of the encircling protection. In the case of asbestos-wrapped cable and a burn-out the speaker would like to know if any of the wrapping has been blown to pieces. Under some conditions there might be a considerable amount of pressure developed in asbestos-wrapped cable, enough, perhaps, to destroy the wrapping.

F. WOODMANSEE: In Mr. Wirt's paper no mention is made of the protection of underground cables by means of static dischargers. The protection referred to being from static accumulations on cables. It is a mooted question whether these static dischargers are useful or not; some engineers are of the

opinion that this kind of apparatus produces more trouble than it prevents.

PETER JUNKERSFELD: For several years we have believed that under our conditions in Chicago static dischargers are, as Mr. Woodmansee intimates, liable to be more troublesome than useful; for this reason we have never installed them. Formerly the pressure was 4500 volts, but during the last two years it has been 9000 volts on our transmission system.

G. N. EASTMAN: The Edison Company is operating a grounded system and the static arresters would have no effect on the system except in case of certain current effects; in that case the energy which the static arresters would be capable of taking care of would be so small that their value would be questionable.

F. WOODMANSEE: Are they not in use on the Manhattan system? Perhaps some one from New York could tell us how they are operating. In the West there are two places where they have been in service only a short time—in Kansas City and Minneapolis. There is some difference of opinion as to whether they are of any value, or whether they are really introducing a number of weak points in the system which would have more serious effects than the static pressure.

PETER JUNKERSFELD: The New York Edison Company, it seems, does not use static dischargers on their 6600-volt, 25-cycle system which is a higher pressure than our old 4500-volt transmission, nor do they ground the neutral. In Chicago, since raising the pressure to 9000 volts, we have grounded the neutral.

H. B. ALVERSON: Referring to static dischargers, we have a system of between 40 and 50 miles of 11 000-volt cables and have no static dischargers. In about eight years' experience there have been but two instances where static dischargers might have been a possible benefit; that is, more than one cable giving out at the same time for the same cause.

CHARLES F SCOTT: Mr. Buck, of the Niagara Power Company, has said that he did not use static dischargers on the Niagara system and did not think it worth while; that he thought best to leave out as many of the safety devices as possible, as a safety device was apt to give more trouble than it prevented.

G. R. RADLEY: In Milwaukee static dischargers are used because the ozone had apparently formed an acid at certain places in the rubber cable, and at the hard-rubber bushings in several switches. Since installing them this effect has not been noticed, but since the neutral of the generators was grounded about the same time it may not be fair to give the credit entirely to the dischargers.

G. N. EASTMAN: On a system which is operated without a ground static arresters may be of some value. In one case with which the speaker is familiar, five miles of rubber-insulated, lead-covered cable was used, and many cases of trouble occurred. Lightning-arresters were installed and no benefit was noticed, but when the neutral was grounded the trouble disappeared.

A paper presented at the 189th Meeting of the American Institute of Electrical Engineers, St. Louis, Mo., Sept. 14, 1904.

Copyright 1904 by A. I. E. E.

PRESIDENT'S ADDRESS.

BY BION J. ARNOLD.

Eleven years ago this summer it was our privilege to meet under the auspices of a great Exposition, located upon the shores of Lake Michigan, organized not only to commemorate the 400th anniversary of the discovery of this country, but also to direct attention to the advancement made in the various fields of the world's activities, and especially in those arts in which we, as workers, were most interested.

To-day we meet under the auspices of another great Exposition, brought into being to commemorate the 100th anniversary of the peaceful acquirement by the Government of the United States of a large portion of the territory now contained within its borders, to have our attention directed to the development of the various industries of this and other countries that have taken place during the intervening years.

For a few years preceding the former Exposition, engineers and other engaged in electrical pursuits had had their energies absorbed in attempting to show the owners of street railways that operation by electricity was cheaper and better than by means of the horse or the cable. We, at that time, had seen the horse practically disappear from street railway service and the cable supplanted in some instances.

The more ambitious engineers were then advocating the use of electricity on elevated railways, and making figures to prove to the owners of such railways that electricity was cheaper in operation and more desirable for such conditions than steam locomotives, then universally used for such work.

At that Exposition was placed in operation an elevated electric road, known as the Columbian Intramural Railway, which though the Central London Underground, a road of light equipment, was started some time before, and the Liverpool Overhead Road soon after, was the first practical commercial application

on a large scale of electricity for the propulsion of heavy railway trains. The success of these roads gave the electric railway industry an impetus which has since resulted in the abandonment of steam and the adoption of electricity on every elevated railway now in operation, and practically on all of the underground roads, thus effectually proving the soundness of the theories of those engineers who pinned their faith to the correctness of the conclusions which their figures showed, and who staked their reputations upon the future to prove them true.

The interval between these Expositions has also been one of great activity and development in the field of interurban railways, which has brought into being the extensive use of the alternating current, rotary converter sub-station system of operating direct-current roads, resulting in the interlinking of thousands of cities with each other and intervening points, thus not only affording a new field for the investment of capital but bringing to most of the inhabitants of the territory through which these roads pass greater facilities for the prosecution of business and the widening of their social life.

With the introduction of the suburban railway came an increased volume of passenger travel, induced by the increased facilities, which may well be noted by the managers of great steam railway properties as an example of what may be expected in increased revenue when frequent and pleasant service is available to the public.

The energies of those engaged in electrical industries have thus far been absorbed in fields which now seem to have been naturally theirs, and their success has been such that they now aspire to enter the field occupied by the steam locomotive as a legitimate field of conquest.

The question now is whether this field is one in which the advantages of electricity will be sufficient to overcome the obstacles which seem almost unsurmountable, and enable it to win as it has in the cases cited.

Those who have given the subject little thought or who are unable to analyze it carefully on account of the lack of the technical knowledge necessary to apreciate the difficulties to be overcome, are most apt to predict the early supremacy of the electrically driven train over the steam locomotive.

That the fields referred to have been apparently formidable yet quickly overcome is not necessarily proof, or even good evidence, that the legitimate field of the steam locomotive can be entered and successfully achieved.

Those most familiar with the subject are now prepared to admit that our great steam railway terminals, where many switching locomotives are shunting back and forth continuously, and those portions of the steam roads entering our great cities, where suburban trains are numerous, frequent and comparatively light, can be more economically operated by electricity than by steam. This is evident to most of those engaged in the work, for the reason that it simply means duplicating, on a large scale, the systems which have proven successful in our street railways, operating, as they do, numerous units running at frequent intervals.

Proof that this field is recognized as a legitimate one for electricity is furnished in the examples of steam railway terminals that are now being equipped electrically, such as the lines of the New York Central and Pennsylvania Railroad Companies in the vicinity of New York, involving an expenditure of something over $70,000,000, where not only suburban service will be operated electrically, but where in the case of the New York Central, the main line trains will be brought into the city from points 30 to 40 miles distant.

While these are great examples of electrical operation on steam railroads, and heroic instances of faith on the part of the railway managers in the ability of electricity to successfully meet the conditions of steam railroad work, where the trains are sufficiently frequent, they are by no means conclusive evidence that electrically propelled trains can be made to successfully meet the conditions of trunk line passengers and freight service, the field now so successfully held by the steam locomotive.

The best conditions for electrical success are a great number of units moving at a practically uniform schedule, at equal intervals, within a limited distance.

The legitimate field of the steam locomotive is now one in which there are few but heavy units moving at uneven speeds over long distances at unequal intervals and at high maximum speeds.

The amount of energy transmitted to any great distance and used by electric cars that have been put in use until recently has been small when compared with the amount of energy that it takes to propel a steam railroad train of five or six hundred tons weight at the speeds ordinarily made by such trains.

It may be taken as axiomatic that when investment is taken

into consideration, power cannot be produced in a steam central station, under conditions that exist to-day, and transmitted any great distance to a single electrically propelled train, requiring from 1000 to 2000 h.p. to keep it in motion, as cheaply as a steam locomotive, hitched directly in front of the train will produce the power necessary for its propulsion. Therefore, there must be other reasons than the expected economy in power production to warrant the adoption of electricity on a trunk line railway unless it can be shown that the trains are frequent enough to make the saving in the cost of producing power greater than the increased fixed charges made necessary by the increased investment due to the adoption of electricity.

There are undoubtedly in existence to-day conditions where water power in abundance is available along the right of way of existing roads, in which the substitution of electricity for steam could be made a paying one, with apparatus now available, even on roads having a comparatively infrequent service, but these are special cases and only tend to prove the correctness of the position, for in these special cases the cost of power would be but little over half the present cost of producing it by means of a central steam-driven station.

The ideal conditions for any trunk line railroad having a traffic heavy enough to warrant the investment in a sufficient number of tracks to properly handle this traffic in such a manner as to get the most efficient service out of its rolling stock, would be to have four or more tracks between terminal points, upon which, in pairs, could be run the different classes of service at uniform rates of speed. Thus, if six tracks were used, the through line, passenger, and express service would be run on one pair of tracks; the local passenger, local express, and local freight service upon another pair of tracks; while the through freight service would be run upon a third pair of tracks, and all the trains upon any pair of tracks would run at the same average speed and stop practically at the same places.

If these conditions could prevail and the traffic were sufficient to warrant this investment in tracks, such a service could be operated more economically and more satisfactorily electrically than by steam.

The difficulty is that few roads in existence have sufficient traffic to warrant such an investment in permanent way, and the result is that all of their traffic must be handled over one or two tracks, thus necessitating trains of all weights and all

speeds running upon the same rails. This results in a tendency to bunch the cars into as few trains as practicable, in order not only to reduce the cost of train service to a minimum but to give the fast-running trains greater headway to allow them to make their time safely. Such an arrangement of trains necessitates the concentration of large amounts of power in single units, which is leading away from the ideal conditions for the application of electricity to the propulsion of trains; and it is this element, combined with the fact that the traffic on most roads is not great enough to warrant the investment necessary in electrical machinery to produce and transmit the power to the distances necessary to keep a few heavy trains in motion, that makes the trunk line railway problem so difficult, as it is more economical to propel these heavy trains by steam-driven locomotives, which are practically portable power-houses.

It being admitted that electricity becomes most economical when a sufficient number of trains are available, and that the steam locomotive is most economical when the trains have become few and heavy, the problem then resolves itself into one of the density of traffic and the question then is: where is the dividing line?

It was my intention to attempt such an analysis of this subject as to be able to formulate some general law which could be readily applied to any given case, and thus enable one to decide whether electrical operation would be more economical than steam in any concrete case.

After carefully analyzing the subject I have become convinced that no general law or formula can be laid down which will apply to all cases, for the reason that the elements entering into different cases vary so greatly that any formula would contain too many variables, dependent upon local conditions, to admit of a general application.

I shall, therefore, only attempt to point out a way in which the dividing line between steam and electricity can be determined after the elements of each case are known.

It will readily be seen that with steam locomotive operation the fixed charges, and cost of fuel and engine labor increase almost directly proportional as the train miles increase, for in this case an additional locomotive means simply a given amount of increased investment, a given amount of increased fuel and labor, and this total investment is least when the number of locomotives is small.

On the other hand, with electricity it is necessary to invest at once a large amount of capital in the power houses and transmission systems, which amount must be great enough to provide for handling the maximum number of trains required upon the line, and unless this number of trains is great enough so that the economy effected in the different method of producing and applying the power is sufficient to offset the increased fixed charges, due to the additional invested capital, it will *not* pay to equip and operate electrically.

Any problem, therefore, must be analyzed for the relative cost in operation. In case this does not show a saving the advisability of equipping electrically will depend entirely upon the probable increased traffic to be derived from the adoption and operation of electrically propelled trains.

That electricity will be generally used on our main railway terminals, and ultimately on our main through lines for passenger and freight service, I am convinced, but I do not anticipate that it will always be adopted on the grounds of economy in operation; neither do I anticipate that it will come rapidly or through the voluntary acts of the owners of steam railroads, except in special instances.

At first the terminals will be equipped for special reasons, due either to the voluntary act on the part of the terminal companies to effect economy in operation, or to public pressure brought to bear upon the owners through an increased demand on the part of the public for better service, on the grounds that the use of the steam locomotive is objectionable in our great cities.

These roads which run through populous countries will either build new roads, or acquire, for their own protection, these electric railroads already built and operating in competition with them, and utilize them as feeders to their through line steam trains. Thus the steam railroad companies will gradually become interested in electric railways and eventually become practically the real owners of them. With these roads operating as feeders to the main line system and with the terminals thus equipped and the public educated to the advantages of riding in electrically equipped cars, the next step will logically be the electrical equipment of the trunk lines between the cities already having electrical terminals.

Thus some favorably located trunk line having a sufficient density of population will feel warranted in equipping elec-

trically, and when this is once done the other roads running between the same competing points must, sooner or later, follow in order to hold their passenger traffic.

This may result in temporarily relegating some roads to freight service, so long as they operate exclusively by steam, but with the increased demand on the part of the public for better and cleaner service will come a corresponding increase in passenger revenue to the roads equipped for handling it until one road after another finds it advantageous to furnish an electric passenger service.

With the terminals and main lines equipped electrically, and the desire on the part of the public for more prompt and effective freight service resembling that which is given by the steam roads in England and on the Continent, due to the great density of population, there will be developed a great high class freight service conducted in light, swiftly moving electric trains which can be quickly divided and distributed over the surface tracks of our smaller cities, or through underground systems similar to that which is now being built in Chicago. Such a system would soon prove indispensable to the public and a source of great profit to the roads as it is now getting to be to many suburban railways.

This class of freight service would soon prove so large a part of the freight traffic of a road that the operation of the through freight traffic by steam locomotives, though at present cheaper, would in time, as the cost of coal increases, grow less, until those roads operating an electric passenger service would ultimately use electricity exclusively.

It has not seemed advisable to me in an address of this character to attempt to furnish detailed figures to support my theories for the subject is of such general interest that many able men are presenting papers upon it at the International Electrical Congress now in session here, in which papers will be found information of much value to those interested, and from which I believe the correctness of some of my assumptions can be proved.

The principal problem before the electric railway engineer to-day is how to make the most effective use of the high-pressure transmission, and high-tension working conductor and maintain safety of operation.

Experiments conducted during the past year by engineers in this country and abroad have made this problem simpler

than it seemed before and to-day we seem reasonably certain of the solution.

Until recently the cost of electrically equipping a trunk line under the standard direct-current, rotary converter system, has been such as to practically prohibit its adoption, but recent developments in the single-phase alternating-current motor field have made it possible to eliminate a large part of the investment heretofore necessary and the prospects for the application of electricity to long-distance running are better than ever before.

When it is recalled that the rotary converter, which was the means of reducing the cost of long-distance roads, was introduced in 1898, and that within the six years from the time of its adoption through the development of the single-phase motor it has been practically rendered obsolete for heavy railroad work, it will be seen that the dividing line between the steam locomotive and the electrically propelled train has moved several points in favor of the latter, due to the reduction which can now be made in first cost and the saving in operating expenses.

With the single-phase motor and the steam-turbine a reality, the transmission problem almost solved, and with the rapid development of the internal combustive engine now taking place, are we, as engineers, not warranted in believing that we can so combine them into a system which will ultimately supplant the steam locomotive in trunk line, passenger and freight service?

I do not anticipate that all roads will soon adopt electricity, for the steam locomotive will hold its field in this country for many years to come, but I do expect, judging somewhat from "positive knowledge," a remarkable development to soon begin in the electrical equipment of favorably located steam roads.

From Richmond, where the first commercial electric road was built, to the present is but 17 years, yet within that time the horse has been relegated to the past as a serious factor in transportation, the cable has served its usefulness and awaits its end, and the suburban railway has been developed and is now rapidly encroaching upon the field of the steam railway.

With the terminals of the two greatest roads in the United States now being equipped electrically and with an investment of something more than $4 000 000 000 in electrical industries

made within a quarter of a century, we have reason to feel satisfied with the past.

With several of the leading roads in this country, of England, of Sweden, of Switzerland, of Italy, and Australia electrically equipping branch lines and seriously considering changing large portions of their present systems from steam to electricity, we, as personal factors in this great industrial advancement, have every reason to be hopeful for the future.

Discussion on "Different Methods and Systems of Using Alternating Current in Electric Railway Motors."

Mr. Steinmetz: The problem which we have before us here for discussion—the problem of the direct application of alternating currents to electric railways—is not a new one, but it has become of primary importance and interest in the last few years. The early pioneers in electric railroading, 10 or 15 years ago, started the development of the alternating-current railway motor, and prominently among them may be mentioned Mr. R. Eickemeyer and Mr. Vandepoele, who designed alternating motors for railway purposes and investigated their characteristics. However, very little progress was made in this field for many years, for a number of reasons; one being that in those early days frequencies of 125 to 130 cycles were customary, far higher than we are using now, and the difficulties of the problem were thereby increased so formidably that advance was necessarily very slow. In addition, the very rapid development of the direct-current railway motor fully occupied the attention of all electrical engineers, and therefore the less urgent field of the alternating-current motor was necessarily somewhat sidetracked. Then the alternating-current polyphase induction motor came into the foreground, showed its superiority over other types of motors for stationary work, and impressed the engineers to such an extent that for a long time it overshadowed the work done by the early investigators on the variable-speed alternating-current motor; that is, on motors with series characteristic. Attempts then were made to introduce this very successful polyphase induction motor into electric railway work, attempts which have not been successful to any great extent. In the meantime, in the United States the synchronous converter was developed and became a standard piece of apparatus familiar to everybody—standard as much as the direct-current generator and the alternating-current generator; and experience with such synchronous converters shows that for electric railway work, for the violently fluctuating loads on the railway system, the synchronous converter is superior even to the direct-current generator: the absence of armature reaction, the phase control of pressure feasible in the converter, and corresponding close pressure regulation, make it specially able to withstand and take care of very violent fluctuations of load and to carry overloads which no direct-current generator can carry. This apparatus became standard, and with its introduction the field of the direct-current railway motor could—the distances which could be covered by the direct-current railway—was extended practically without limit, and a field opened which has been exploited in the last years, which was the field dreamed of by the early pioneers; the difficulties, however, being overcome, not by the development of the alternating-current motor, but by the development of methods of transmitting alternating currents and transforming

them into direct currents along the routes, in synchronous converter sub-stations.

Now, however, in the last year or two, with the still further development of the electric railroad, we have approached and in many instances reached the limits of applicability of this synchronous converter. The synchronous converter is a piece of machinery which requires sub-stations, requires some attendance, and as a necessary result has a high economical efficiency only where the traffic is sufficiently condensed to warrant the maintenance of sub-stations within relatively short distances from each other. Where the number of trains is less or the power per train greater than can be supplied at 500 volts from sub-stations, without excessive expenditure in line conductors, and too excessive fluctuations of load, pressures are required higher than can be utilized efficiently in direct-current motors, and there we strike the limit of the synchronous converter, and the alternating-current motor has to come in.

Personally the speaker does not believe that the alternating-current motor will make very serious inroads in the field now occupied by the direct-current railway motor. Nor does he believe that direct-current railway systems will be changed into alternating-current railway systems; but what he expects of the alternating-current railway motor is that it will find a field of its own, a new field: just as when the alternating-current method of distribution was developed in this country, it did not displace the direct-current method of distribution which occupied the centers of our large cities, but it found a field of its own, a field which has gradually developed so as to be equal in importance if not superior to the field occupied by the direct current. Hence, to conclude these remarks, what the speaker expects of the alternating-current railway motor is that it will find and develop a field of its own, that field which the direct-current railway motor cannot reach—suburban and interurban service, long-distance service, secondary railway service.

When considering the technical aspect of the subject before us for discussion to-day, the relative advantages and disadvantages of the direct- and alternating-current railway motors, we have to consider, first, the character of the problem we have to meet in electric propulsion; secondly, the character of the apparatus which we have available to solve these problems; thirdly, the additional features imposed upon the problem, or conditions more or less outside of the problem, as, for instance, the condition of the electrical industry at present, the existing investment in direct current and in steam railroads, which have to be taken into consideration when discussing any new system of railway propulsion.

Regarding the characteristics of the different types of motors —the direct-current series motor now in universal use for railroad work, the polyphase induction motor proposed, and, to a certain extent tried in the last years for railway work, a

motor eminently successful in stationary work—and the alternating-current single-phase railway motor with commutator, the speaker has, in a paper before the International Electrical Congress, given the results of a theoretical investigation and discussion of these different motors and shown the speed-torque curves, or characteristic curves of these motors in relation to each other. In Fig. 1 is given a comparison of the typical speed-torque curves of the different types of motors.

In general, the characteristic of the polyphase induction motor is essentially that of a constant-speed motor, with shunt-motor characteristics; that is, it can efficiently operate over a certain limited range of speed only, cannot exceed the synchronous speed, and when operating below its normal speed, it operates less efficiently; that is, when operating at a lower speed than normal, or approximately synchronous, as can be done by a rheostat in the secondary circuit, the polyphase induction motor merely wastes that part of the power corresponding to the difference between its actual speed and synchronous speed. Or in other words, at low speed the induction motor consumes the same power which it consumes with the same torque at full speed, though its power output is reduced in proportion to the speed, and its efficiency correspondingly.

In the direct-current series motor the torque developed by the motor decreases with increase of speed, and inversely with increasing load the speed of the motor decreases. The maximum torque of such a motor occurs in starting. All variable-speed commutator motors, alternating and direct, more or less differ from each other in the rate at which the torque varies with the speed, and that brings us to a consideration of the requirements of electric propulsion.

Important classes of work to which an electric motor may be put in locomotion are: first, city railway or tram-car work; secondly, rapid transit service as on elevated and underground roads; thirdly, suburban and interurban service; fourthly, trunk line passenger service; fifthly, long-distance freight service, and sixthly, elevator service.

Now, discussing these briefly in succession. The city tram-car service is characterized by frequent stops of irregular duration, at irregular intervals. To maintain good average speed it is therefore essential that the motor should get under way after the stop as rapidly as possible; that is, have a very high starting torque and accelerating torque, and carry this high torque up to a considerable speed. Beyond this speed, then, the torque of the motor should decrease fairly rapidly down to the torque required to run on a level track, which we may assume roughly to be at twice the speed to which the high torque of acceleration should be maintained. In addition thereto, it is necessary that the motor should accelerate efficiently and that it should be able to operate efficiently at low speeds in those city districts where the general traffic is dense

and where it is not possible to run at high speeds. The characteristics of this type of motor are preeminently given by the direct-current series motor. If we assume the torque required to run on a level track as 1, probably the starting or

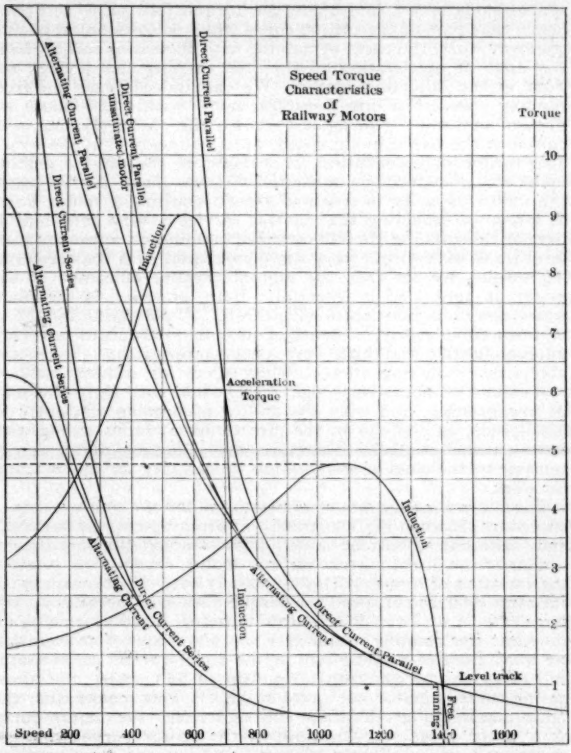


FIG. 1.

accelerating torque may be something like six times as high. At that torque we start and run up to considerable speed, and then strike what is called the *motor curve*, and after cutting out all regulating devices, accelerate with decreasing velocity

up to the free-running speed. Such a curve, that of a typical direct-current railway motor, is given in Fig. 1, marked "direct-current parallel" and "direct-current series." The induction motor, although it may accelerate with a high torque, at the end of acceleration, the speed is limited. It accelerates up to or near synchronous speed, and there the torque falls off to zero; and hence that part of the torque curve which is so essential to city tramway work, the curve of running with decreasing torque, from the limit of acceleration to the free running speed, does not exist in the induction motor. We can indeed reach the free-running speed of a direct-current motor with a polyphase induction motor by gearing it to twice the speed, making synchronism the free running speed, but this means that the available torque of acceleration, and therefore the rate of getting under way, is reduced by one-half or if we make it the same, the motor capacity is twice as great, requiring a motor twice as large. Considering that in this service a very considerable part of the running time is occupied running on approximately level track with torque very small compared with the accelerating torque, we see that the highest possible efficiency of the motor at light load is essential. Here, however, is the place where the induction motor falls down. A polyphase induction motor running at, say, one tenth of its maximum output runs very uneconomically and with very poor power-factor. So in the polyphase induction motor, when used for railway service, you cannot combine very high acceleration with high efficiency in free running, and with the ability of running efficiently at low speeds, as you can in the direct-current series motor with series-parallel control. Therefore, the induction motor is not suitable to the class of work which we call city service or tram-car work.

The alternating-current commutator motor of which two sets of curves are shown in Fig. 1, marked "alternating-current parallel" and "alternating-current series" has characteristics very closely similar to the direct-current railway motor, except that possibly the variation of torque with the speed is less. That means, with the same decrease of speed the torque does not increase at the same rate as with the direct-current motor; if we assume again the same free running torque as 1, and the torque of acceleration six times the free-running torque, the direct-current series motor will carry the acceleration torque up to half speed; the alternating-current motor not quite as high. This means with the same maximum acceleration you will strike the motor curve at a lower speed, accelerating on the motor curve, you get under way, then, slightly slower, or to get the same average acceleration you have to start with a higher maximum acceleration. Now, this is an advantage in some cases in so far as you run for a longer period of time and over a wider range of speed on the motor curve, that is without controlling devices, hence in the most efficient manner possible, and thereby make up

to a considerable extent for that power which the alternating-current motor inherently loses by its slightly lower efficiency due to the alternating character of the magnetic field, and the losses by magnetic hysteresis in the motor field of the alternating-current motor which do not exist in the direct-current motor. This difference in the speed-torque curve of the alternating-current series motor, compared with the direct-current series motor, is due to the lower magnetic density used in the alternating-motor field, and, at low speeds, also to the e.m.f. of self-induction. The first phenomenon, therefore, also occurs in an unsaturated direct-current series motor (Fig. 1), and such a direct current series motor therefore has at high and medium speeds the same characteristic as the alternating-current motor. It is undoubtedly true that alternating-current motors can be designed to give very closely the same characteristics as the standard direct-current series motor. However, the motor as it is before us at present reaches the motor curve at a lower speed, therefore with the same maximum acceleration, gives a lower average acceleration up to full speed, or with the same average acceleration requires slightly higher maximum acceleration.

Coming now to the second class of service, rapid transit service, here the problem and the conditions of operation are almost identically the same as in city service, except that the units are larger, the speeds are higher, the stops not as frequent, absolutely, but about just as frequent relatively in comparison to the maximum speed of the motor, so that we can directly apply our considerations to rapid transit service—regarding a comparison of polyphase induction motors of alternating-current commutator motors, and of direct-current motors.

In interurban and suburban work, that is, in railroads running out from the cities far across the country into the suburbs or into other cities, we have a much lesser frequency of stops. That means that rapidity of acceleration is of lesser importance, and we can well get along with a lesser average torque of acceleration, but we must have the same surplus torque as on city service work, or rather a greater surplus torque, because, while in city service and in rapid transit service where the distances are relatively short, we can count on maintaining fairly constant pressure in the supply system, we cannot to the same extent count in this on interurban and suburban service where we are far away across the country, except by investing much greater sums in line conductors and feeders than is commonly economically desirable or feasible. Hence, in this service the motor should have a greater surplus torque than in city service, so as to get a sufficient margin to start the train or the car under the most severe conditions on an up-grade or an overload, even if the pressure in the system is low. The motor which is most sensitive to pressure variation is the polyphase induction motor. The maximum torque which this motor can

give necessarily cannot very much exceed the acceleration torque without badly spoiling the characteristics of the motor either electrically or mechanically; but the maximum torque varies with the square of the pressure and hence rapidly decreases if the pressure of the system is low. In the motors with series characteristics, however, like the single-phase commutator motor, the direct-current series motor, the torque does not depend on the pressure; or rather, while the maximum torque so depends, the theoretical maximum torque which you get from the motor when standing still is so far in excess of the torque of self-destruction, or rather of slipping the car wheels, that it is not reached, and the effect of variation in the supply pressure is merely a variation in the motor speed. That is, if the pressure is low in the system, the direct-current motor and the alternating-current commutator motor runs at lower speeds, but still is able to give the same torque, while the polyphase induction motor runs at the same speed, but is not able to give the same margin of torque, and at a certain load falls down or does not start. That means that in designing a system of transmission and distribution for alternating-current commutator motors or direct-current motors we are permitted to design the system for the average drop of pressure in the system while in designing it for induction motor service, we have to take into consideration the maximum drop of pressure in the system which is very much greater than the average.

For interurban and suburban service we require an excess overload in torque, but do not require an acceleration up to high speed. The alternating-current commutator motor appears to be preeminently satisfactory in this work, and there is where the speaker believes it will be used extensively, and where the advantage of a high-pressure trolley and of the absence of substations is specially important.

In trunk line passenger service the rate of acceleration as given at present by the steam locomotive is very much less than every-day practice in electric railroad service. So here we do not need this excess acceleration torque sustained up to high speeds. Here, again, we find a field where we may apply the alternating-current commutator motors. The polyphase induction motors could be used if the question of pressure supply did not come in, as discussed above, and if furthermore the limit in speed of the induction motor was not so objectional in passenger trunk service, where, more than anywhere else, we desire to get the full benefit of the track by running at the highest safe speeds wherever the track is level. This the induction motor with its limited speed cannot do.

In trunk line freight service. the same considerations come in, except there the speeds are relatively low, the train weights great; and it is more than anywhere essential to have a very large surplus torque available to get under way or to hold the train on a grade. You must, therefore, in this class of service,

just as in suburban and interurban service, have a motor running efficiently at light load, but being able to give very high torque, although it does not need to carry this torque up to high speeds. On the contrary, it is not desirable in freight service that the motor should sustain a high torque up to high speeds, because that would mean the consumption of very large power. In freight service the highest possible economy is especially necessary, and the highest possible economy means the least fluctuations of power consumption; that means on up-grades you would desire to go slow and reduce the power consumption and get the high speeds on the level track.

In mountain railways and such classes of work, the running torque is of the same magnitude as the starting torque, and so the load on the motor is more nearly constant than in any other class of railway work, and on the down-grade the motor is preferably used for braking, by returning power into the line. Here then the polyphase induction motor appears well suited, and is indeed being used successfully. Such service, however, is in its character more nearly akin to elevator service than to railway service.

In the discussion so far we have considered the requirements of the different classes of railway service, irrespective of extraneous conditions. When considering the alternating-current motor and the direct-current motor, we have to take in view what exists at the present time in this country and abroad. There exists the enormous network of steam railroad and of direct-current electric railways. The steam locomotive is a unit of very high efficiency, but a very large unit. It therefore for efficient operation requires the massing of traffic in heavy trains, and results in less frequent but large trains. This has practically rearranged and reorganized the whole system of locomotion by collecting it into a small number of very large units. That is not the most efficient manner of operating electrically-propelled vehicles, but rather the contrary. Furthermore, you have to consider that every city and almost every village has a direct-current railway system. Now, the main and most important features by which the electric railway motor and electric propulsion has gained and is gaining rapidly in competition with the steam locomotive, appears to the speaker to be the frequency of headway and the absence of passenger stations, not the speed, which frequently in electric lines is lower than that on steam railways paralleled by them. The electric railway picks up its passengers anywhere in the city and deposits them anywhere and it does not require them to consult time tables, but runs its cars so frequently that the passenger can always find a car within a few minutes at any point; on the other hand, the steam locomotive requires you to consult a time table and go to a depot. As soon as the electric railroad gives up this advantage which has just been mentioned, one of the main advantages of the electric

railroad over the steam railroad will be lost, and this, therefore, is the feature which has to be kept in view. It means that whatever type of motor may be adopted in interurban or suburban service, etc., it must be able to carry the passengers through the cities over existing railways.

The existing railways are direct-current railways, and probably will remain so. That means that the long-distance motor, at least the suburban and interurban motor, must be able to run over the direct-current system. Hence, it must be a type of motor equally applicable and capable of operation on a high-pressure alternating-current or on the 500 volt direct-current system.

Taking this for granted the methods of control must also be as simple as possible, that is, the same control for alternating as for direct current. Even if the motor could be used on direct current and alternating current, if we would have to carry a double system of control, one for city service and direct current, the other for long-distance service and alternating current, this would be a very serious handicap. It means that really to solve the problem before us, or extending the electric railroad into interurban and suburban service, and into the field now occupied by the steam railroad systems, and into new fields not yet developed, to a large extent not even dreamed of, that we must have a motor which with the same controlling appliances and the same characteristics, can run either on the high-pressure alternating circuits or on the existing direct-current circuits.

Furthermore, the enormous investment in electric railway systems existing at present has all been made, in the large systems, on 25-cycle, three-phase apparatus. That means that we shall have to continue to operate at 25 cycles. It may be preferable, possibly, to run at lower frequencies, or it may be preferable to run at higher frequency in this instance or that instance, but regardless of whether it is preferable or not, if it can be done on 25 cycles, it will have to be done on 25 cycles, and if another frequency had to be used, it would be a very severe handicap to the new system. The speaker is glad to say that there is no doubt that 25 cycles is the frequency best suited to the alternating-current single-phase railway motor.

PRESIDENT GRAY: Dr. Steinmetz's remarks have been so clearly stated and so closely reasoned out that they do not give us much chance for discussion, but the speaker is glad to refer to an English colleague, Professor John Perry, upon whom he calls to take part in this discussion.

PROFESSOR PERRY: The speaker has to confess that he is not prepared to take part in the discussion. We have had the address of President Arnold and this excellent address of Professor Steinmetz, and two such addresses in one morning we have never had before. Clearly, they are men who have thoroughly studied the subject of traction, and it seems to the

speaker that they have both come to the conclusion that the electrification of steam railroads in the next ten years depends on the success of the single-phase alternating-current motor. Of the progress that has been made by the General Electric Company and the Westinghouse Company, in getting such motors to work well, the speaker had heard a great deal before leaving the other side, and it is one of the things that he promised himself to learn something about during his visit here. He has not yet been able to do much in the way of getting accurate knowledge on the subject. He has been on a tram-car at Schenectady, the motor of which was driven by direct current and the car ran well; and then he would get on another car, and was told that the motor was driven by alternating current, and it seemed to run just as well. He had no means of experimenting or ascertaining what the efficiencies of the various arrangements were. Some 10 or 12 years ago he was greatly interested in the single-phase alternating-current motor, perhaps for a selfish interest, as he had invented a system of traction which required the use of that system. That interest is increasing. The speaker wanted to go to the section in which Mr. Steinmetz was giving an account of the work yesterday, but was told it was his duty to attend a discussion upon the subject of electromagnetic units in another section, and as a man cannot be in two places at once, the doing of his duty robbed him of a great pleasure. In these circumstances, he can only say that he should like to hear the discussion of this subject proceed further before he shall feel able to take any part in it.

B. G. LAMME: Away back in the dark ages of electric traction, about 15 years ago, there was great confusion in the types of apparatus used. There were all kinds of motors and all kinds of apparatus on the car. They only had one property in common—they were all direct current. After putting a number of these systems into commercial use it was discovered that certain types of apparatus were superior to others, and those particularly interested in the manufacture of such apparatus followed up this matter to ascertain what properties were of the greatest value. It was gradually discovered that one type of motor was taking precedence of all others, namely, the series motor. Practically all development for a certain time was in the direction of the direct-current series motor.

The reasons which led to this were partly based on theory and partly on practice. The series motor gave the effect of a cushion on a car. The motor is inherently a variable-speed machine and automatically varies its speed with the condition of the load. That was discovered to be a matter of first importance in the smooth operation of electric cars. Also the motor automatically increases its torque in a greater proportion than the current, which is of great importance in regard to

starting and acceleration. These points were possibly not as well understood at that time as at present, but experience showed that certain equipments were superior to others and development was along that line.

After a few years, when the motors had reached standard proportions and practically but one type was used, a second limitation was discovered; namely, in the transmission conditions. It was found that in the extension of the railway system, the ordinary 550- or 600-volt direct-current system was becoming cumbersome, and it was evident that some method of transmitting power at higher pressure and transforming to lower pressure for utilization would be necessary. The most evident method was naturally to transmit by alternating current and convert to direct current, in order to use existing car equipment. This led to the use of motor-generators, and later to synchronous converters.

The motor-generator was found to fit the existing alternating system fairly well, but in the development of the synchronous converter the manufacturers discovered a great difficulty in existing systems. The frequencies of 125 and 133, which were the standards for many plants, were entirely unsuited for synchronous converters and also not well adapted for synchronous motors. Another frequency, coming into general use, namely, 60 cycles, was found to be possible for use with synchronous converters, but the difficulties of design were very great in that case, and the synchronous converters were rather heavy and cumbersome.

At that time there was fortunately a new frequency adopted which was of prime importance in the development of the synchronous converter, namely, 25 cycles. So far as the speaker knows, the origin of that on a large scale, was as follows: in the Niagara Falls power plant, when it was first laid out, the engineers for the power company had arranged for a frequency of 2000 alternations per minute, or 16⅔ cycles per second. They wished to use 8-pole machines, running at 250 revolutions. The company which the speaker represents, which was one of the prominent bidders on the contract, objected seriously to the proposed frequency, as it was considered entirely uncommercial and also not suited for the best design of machine. The engineers of this company recommended 4000 alternations per minute or 33⅓ cycles per second. That was considered extremely low compared with anything then in use. As we could not come to any agreement to use that frequency, we finally compromised on 3000 alternations per minute, or 25 cycles per second, and the first Niagara machines were built in that way. There were various reasons for the adoption of a low frequency, one of which was that commutator type of motors might possibly come into use. Another reason was that it was better adapted to synchronous converters, but it was admitted that 33⅓ cycles would also be satisfactory.

After the Niagara Falls plant was installed, there was then a precedent for the adoption of this frequency for large units, and the manufacturers began to build apparatus of this frequency for the Niagara Falls plant and also adopted it for other plants. This opened quite a field for the synchronous converter and it soon began to be extensively used for railway work, as it was recognized that this was the link needed for extending the direct-current system. Even at the early date of 1893 and 1894 it was believed by many engineers that the synchronous converter was simply a machine to meet an emergency condition, that it would not last, that the time would come when synchronous converters would be dropped from the railway service, but as the most convenient and apparently the best solution of the problem, it was adopted extensively. About that time electric railway service began to be greatly extended and synchronous converters have thus come into very general use. By the use of synchronous converters, the advantages of the alternating-current system in transmission are obtained and the advantages of the direct-current system with the series motor were retained. Distances could be extended indefinitely by increasing the number of synchronous converter stations and raising the pressure of the alternating-current lines.

Shortly after this system came into general use it was recognized that a purely alternating-current system, in which purely alternating current was supplied to the motors, would be advantageous and considerable work was done along that line. The polyphase motor apparently had the field, and naturally the manufacturing companies took up the question of the application of the polyphase motor to traction work. The company which I represent, the Westinghouse Electric and Manufacturing Company, took up this question in an active way about 1895, and built two motors of 75 h.p. each for traction work. These motors were equipped with collector rings and rheostatic control and tests were made in regard to performance, both with straight rheostatic control and with the now well known "tandem" control, in which the secondary of one motor is connected to the primary of the other to obtain half-speed conditions. Even with this latter arrangement it was found that the motors would not compare at all favorably with the direct-current motor or the system with the direct-current system using synchronous converters, and this work was abandoned. It was recognized that the polyphase motor did not possess the proper series characteristics which long experience had shown to be so necessary for railway work. Other experiments along this line were made, using polyphase motors wound for two or more speeds, and two 100 h.p. motors were built which were wound for several speeds. While this was better than the other arrangements, it still appeared that this was not a solution of the problem. Previous to this time the company had done some work in the direction of using single phase, but not as a solution of the problem which presented itself in 1895 and later.

In 1892 the question of the use of the commutator type alternating-current motor for railway work was taken up. Two motors of nominally 10 h.p. each were designed and built. These were built for a frequency of 2000 alternations per minute, or 16⅔ cycles per second. They were mounted on a car and were operated for a while, but the system was not a success. In the first place the pressure used—400 volts as compared with 550 in the direct-current motor—was rather low. It was considered that as 550 volts was the limit in the direct-current motor, 400 volts would be the limit with alternating current. The motors were tested on a track of iron rails with practically no bonding. The track drops were excessive and the pressure fluctuations were great. The generator used—of about 20 kw. capacity—was entirely too small for this work and it was not adapted to handle the inductive loads which were found with alternating-current motors. A series of tests was run and it was finally decided that for city work, for which the system was then laid out, the motor could not compete with the direct-current motor. It was decided, however, that such a type of motor would probably furnish the solution of the heavy railroad problem, but as there was no such heavy railroad problem at that time, the work was dropped for a while. But in 1897 the question of the use of the commutator type of alternating-current motor was again taken up—this time on a somewhat larger scale. Motors of 50 h.p. were built for variable-speed work, and given a long series of tests. Then after sufficient experience had been obtained, the work was gradually carried to the larger sizes.

In 1900 and 1901, when the question of the polyphase traction in Europe was so extensively advertised, it became evident that there was actually a demand for an alternating-current railway system. It was therefore decided to continue the previous work with large motors of the commutator type, and two motors of 100 h.p. were designed and built. For these also, the frequency adopted was 2000 alternations per minute, or 16⅔ cycles per second. This fractional figure was primarily adopted on account of certain steam-engine conditions. It was recognized that an even frequency of 16 or 18 would have been practically as good.

In the earlier work, with the 10 h.p. motors at the low frequency, it was recognized that it would be absurd to put such a system on the market, as at that time even 25 cycles had not been adopted. The frequencies in common use were 50 or 60 and a drop to 16 cycles was considered prohibitive. In the latter work, as 25 cycles had come into general use, and 15 or 20 cycles had been talked of and proposed by certain companies, it was considered that in view of their advantages for railway work such frequencies should be adopted. The motors were hence built for the above frequency. The results obtained with these large motors were so satisfactory that a contract was taken for

a rather large road and the apparatus prepared. Knowing that news of this would soon be abroad, it was decided that the matter should be brought before the AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS, and a paper was presented on the 26th of September—two years ago—which the speaker believes was the first announcement of the application of the single-phase alternating current to railway motors. There was considerable discussion—mostly criticism—and it was generally considered by the engineering public that the weak point of the system was the commutation. At the present time, however, the speaker believes this is no longer considered as a serious point.

Previous to building the 100 h.p. motors considerable experience was had with the commutation of such motors. Besides a long series of tests, we had run 40 h.p. motors at practically full load on a 60-cycle system for nine months, day and night. At the end of the nine months the commutators were in practically as good condition as in the beginning, showing that the commutator on such machines could be made to have a long life. The conditions of the 60-cycle machines were much worse than on the lower frequency, and the nine months of operation under the condition of steady service probably equalled two or three years of traction service; but the commutator stood up so well that we decided definitely that there was no difficulty on that point.

The principal reasons which led to the adoption of the single-phase motor were stated in the paper above referred to, and were that but one trolley wire would be required and that the motors had the series characteristics. It was considered that no motor, except one of the commutator type, would give suitable characteristics for the service, and it was stated that there were several types of motors, with commutators, which had the proper characteristics. All of these may be classed as series motors, although some of them are combined with transformers and may be considered as transformer series motors, or, under another name, as repulsion motors, and others are pure series motors. The pure series motor is one which can operate on direct current as well as alternating current. The repulsion motor can be modified so as to operate on direct current, but as ordinarily arranged it is not as well adapted for this as the other type. It was recognized in the first undertakings with this system that the motor would probably be required to operate on direct current at times, and the fact that the pure series motor was primarily a direct-current motor of a first-class design was one of the reasons which led us toward the adoption of that type. As both theory and experience indicated that such motors would probably be wound for 200 or 250 volts, it was recognized that the motors would probably have to be operated in series for direct current, and either in series or in parallel for alternating current, as might be desired. The arrangement required for permitting operation on direct current as well as on

alternating are rather complicated, due to the fact that it is neceassry to switch from one system to the other in passing from the alternating to the direct current. We did not suppose that the electrical public would consent to such a combination, but since that time we have found that in some instances they do not object seriously to the increased complication.

At the time that the alternating-current system was brought out it was considered that the principal field would be in heavy railroad work, because this motor furnished what was considered a general solution of the railway problem; as the railroads would have their own terminals and their own rights of way, the system would be an alternating-current system throughout. At the present time, however, roads are being installed which operate primarily on alternating current, but at the terminals and where they pass through intervening towns they operate on direct current.

The direct-current motor has never been considered as entirely suitable for the heavy railroad problem, as usually but two speeds, and at most but three speeds can be obtained with four motors, the third speed increasing the complication considerably. With the alternating-current motor of the commutator type any speed can be obtained for locomotive work, because any pressure can be applied to the terminals of the motor. As soon as alternating current is used for motors, we at once have a ready means of pressure transformation. As on locomotives for large capacity the difficulty of handling the current is considered a very prominent one. it was considered that some form of pressure control which varied the pressure without opening the circuit would probably be the best one. One form of pressure control permissible is what is called the induction regulator. This regulator varies the pressure without opening the circuit. The relation of the primary and secondary windings with respect to each other is varied. This gives a means of varying the pressure to the motors and varying the speed of very large motors with no tendency to sparking at the controller. The only time the circuit is opened is at the end of the operation when cutting it off. Therefore it was considered as an important feature in the solution of the general railway problem.

The single-phase system is the one means presented at the present time as the solution of the heavy railway problem. It has all the advantages of the direct-current motor in the variable-speed characteristic, and has also the advantage possessed by alternating current in the ability to use any line pressure desired, and to vary the pressure applied to the motor and thus vary the speed over any range desired. It also has the advantage of permitting a system of control that can be obtained without sparking.

In the adaptation of the alternating-current motor to direct-current service, two 250-volt motors can be connected in series

for 500 volts; also in operating on alternating current the motors can be connected in series, if desired, or in parallel. There is a possibility of danger in operating two motors in series in this way on alternating current, or even on ordinary direct current. In ordinary direct-current practice the use of two motors in series for part of the service is common practice, but there is this difference between the direct-current equipment and the alternating-current equipment. In the direct current we have motors wound normally for 500 or 600 volts. When operating in series the motors are connected, two in series, each one receiving 250 volts. Therefore, if one motor should slip its wheels and take the full pressure of the pair, it would still be operating at its normal pressure. But with two 250-volt motors connected across a 500-volt circuit, we have a different condition. In case one motor should take the entire pressure, we should have 500 volts across a 250-volt motor. That condition was considered early, and in the Washington, Baltimore, Annapolis project, a description of which was given in the AMERICAN INSTITUTE paper read two years ago, we showed an arrangement by which this could be avoided. Balancing transformers were connected across the two motors in series. The balancing transformer was across the outside terminals, and a tap from the middle of the transformer was connected between the two motors. In this way equal pressure was supplied to the two motors in series, and the danger of a runaway was thus avoided. It is not yet determined how important this is, but the speaker believes that something like this will be found advisable for the operation of motors in series, esepecially where high-power motors are used on medium weight cars for high-speed service. Possibly with comparatively low speed, and with very heavy cars, there may not be the same tendency to slip. On the direct-current part of the road, of course, the balancing transformer could not have any effect; but as the direct current is usually a very small part of the service, this danger would be lessened, due to the proportionate time in service.

In the application of the motor to use on both alternating and direct current, we have found some special conditions which affect the arrangement of control. Take, for instance, a large road being installed between Cincinnati and Indianapolis, where it is intended to run on direct current at the terminals and alternating current on the rest of the line. The normal speed on the alternating current part of the line is so great that it would be prohibited in the towns, and it is found that to get the speed down to the desired rate in the city service on the direct-current portion of the road, it is necessary to connect the four motors all in series, and thus no series-parallel arrangement can be used. Pure rheostatic control is therefore necessary in the city. On the suburban part, a switch is used to throw the current from direct to alternating, simply throwing the four motors in parallel, and taps are used on the lowering

transformers to get a number of pressures. In that way we get the effect of series-parallel control and even better, by having more than two steps. On a long line it is possibly of no great advantage to have many steps, but as a rule the more steps there are, the easier is the service on the controlling apparatus, and the more running speeds are available.

With regard to the application of the system to locomotives, on the steam roads where the systems are not tied up with existing electric plants, it is probable that in time the railroads will adopt their own pressures, and possibly their own frequency. This may not be 25 cycles but may be somewhat lower. The speaker believes that the electrification of the steam road may be a controlling factor in the change from direct to alternating current in city service. If the large railroads with their own large power plants adopt alternating current throughout, then the towns lying along the roads will in time prabably adopt the same power system, and even the large cities will sooner or later adopt the same system. At the present time the railroads, as far as they have gone, have adopted direct current because the cities through which they pass or enter are using direct current. When the railroads make the big end of the project, however, then the cities will adopt what the railroads are using. When this comes about the direct-current railway systems in the cities will be superseded by the alternating.

C. V. DRYSDALE: At this late hour in the discussion, the speaker does not propose to take up your time very much, especially as he is afraid that very few of us over in England have had much experience concerning this important subject. The speaker should like, in the first place, to take this opportunity of congratulating you on this side of the water on having carried this important problem to such an extremely successful issue as has been recently shown in Ballston and in other places. This subject has been worked on in several countries, but to America belongs the honor of having constructed the first line of any considerable length working on the single-phase system. The way in which it has been done is admirable, when we remember that the result has been achieved by getting over the great difficulties that were first encountered with the series motor, and that in so doing it has been found practicable to use the same motive plants on direct- and alternating-current lines. That, in itself, is an enormous advantage over and above that of being able to use the single-phase alternating current.

It would be impossible to criticize any of the statements that have been made this morning, because they come from gentlemen who have had such exceedingly minute experience in the special branch of the subject, that their remarks must be taken as gospel, at any rate for the present.

The speaker's object in taking part in the discussion is rather to bring the matter back to first principles. This subject has been

worked upon in many different ways and although the laminated series motor seems to have been the first to give us results and will probably survive as a practical solution of the problem, yet there are some interesting questions as to whether there are any other ways of fulfilling the requirements which may have other advantages. There is one thing that does not seem always to be sufficiently kept in view in traction matters, in relation to the starting of the cars, and that is the very simple matter that in the starting of the car you do not require power, you require force. If you wish to get anything into motion, what you require in the first instance is purely force, and until the body moves it does not require power at all. One of the great advantages which the steam-engine has over any electrical system up to the present time, is the fact that when steam is first admitted into the cylinder you get the pressure on the back of the piston and get the starting force without taking any power from the steam. If it were not for the other disadvantages of the locomotive, there is no question that this one feature would give it a superiority over anything we have of an electrical nature, because if we turn to the ordinary direct-current motor, we find that we have to use half, or with one motor, the whole, of the full-load power merely to secure full-load torque. This has several objections. Not only is this uneconomical and wasteful of power, but it throws a sudden strain on the generating plant, and furthermore the unnecessary power has to be wasted in resistances, and these resistances sometimes attain a considerable magnitude. With alternating-current motors these evils are worse although less power is taken, as we then have low power-factors and consequently difficulties in regulation.

The time is too short to refer to many other systems, but the speaker will mention one, that known as the Ward Leonard system, which at first sight appears to be an unpromising one. In the Ward Leonard system, as the speaker understands it, the system is to use a single-phase motor coupled to a direct-current generator which supplies direct current to the car motor. Of course, the indirectness of the method seems to put it at fault, but on the continent that method has been developed with considerable hope of success, in fact with considerable practical success; and it has this great advantage that by the use of this arrangement you can get your starting effort with very small power taken from your station. In this system—it is too well known to be described here—you have your single-phase motor continuously running, and you can do the whole of the regulation of your speed, etc., by merely regulating the excitation of the generator. The result is that it is possible to get the full starting effort with only something like one-third or one-quarter of the full-load current on the motors. That is so important a matter, especially in view of the huge trains liable to be thrown on the plant in the

large schemes which we are hoping to see realized in the future, that we should give that method the consideration which it deserves, although it at first sight appears to be roundabout. In addition to that, we have the magnificent system devised by your President, Mr. Arnold, and the speaker hopes we shall hear more of that in the future. The speaker's chief object in rising was to ask that we should hear as much about these systems as possible.

PRESIDENT ARNOLD:—The speaker is pleased to be put down as one of the speakers on this subject, but Messrs. Steinmetz and Lamme have so thoroughly covered the subject, and Dr. Drysdale has so kindly referred to the other systems known to most of you, that it is not necessary to say much more, particularly as the time is growing short.

One statement by Mr. Lamme, rather puts the speaker on the defensive. The speaker understood him to state that his announcement of the single-phase motor made in September 1902 was the first announcement of a single-phase system. In the month of June preceding, the speaker read a paper on a single-phase railway, known as the Lansing, St. Johns & St. Louis Railway, which was built at that time and which has since been put in operation. The speaker does not think it is just for the statement to be placed on record just in the manner in which it was made. Perhaps Mr. Lamme meant to say that his paper was the first formal paper on the subject, but the speaker's road was built and almost ready to operate at the time that he made his announcement.

F. J. SPRAGUE: The subject on the card is how best to use the alternating current in railway motors. It is largely a technical question. The alternating current motor is like a somewhat brilliant boy, who being exposed to various diseases has contracted a number of them; he has had a moderate experience in mumps and measles, and a touch of typhoid fever, and the various doctors, many able ones here and elsewhere, have administered, sometimes in homeopathic but oftentimes in allopathic doses, large measures of quinin and other drugs. Whether, as the child grows—and we are all hopeful of that child—and he is subjected to the various climatic conditions of commercial introduction and use, those undercurrents of disease common to all fevers will recur, or whether the child will outlive them and become strong and robust is a matter which must be left to future developments.

There is a larger problem. It is perhaps a more popular one, but of vital interest to us as engineers who are called upon to advise managers and others as to their financial expenditures, and that is: will electricity be used on trunk lines? Our worthy President, with whom the speaker has the honor to be associated on some important work in that line, is very hopeful, and so is the speaker. But what are the reasons which may dictate the adoption of electricity on trunk lines?

Will it be because an economical service cannot be gotten by steam? No. Will it be because there cannot be obtained to-day an efficient service? Again, no. Will it be because of aesthetic reasons? Distinctly not. If electricity be adopted on any trunk line service it will be because of the hard and fast rule of financial necessity, not because we engineers urge it. It will be because the men who raise the money, run the road and have to provide dividends find that it is the best way to do it, and the reasons which will apply to one road are not necessarily those which will apply to another. It is the speaker's belief that some of the largest expenditures, and those most fruitful of return to those who own the steam railroads of the country to-day will be for the purchase and control of competing electric railways which, having in the past acquired franchises of undoubted value which cannot be duplicated, have built up a profitable business which they can hold and which will increase. Many a steam railway will be better off financially and get bigger returns if it gathers in these franchises and systems, and operates its whole property with proper regard to the needs and capacities of each division than by electrification of its main lines, at least for a long time to come.

ELIHU THOMSON: It is certainly a pleasure to listen to a discussion of this kind in a joint meeting of the Institution of Electrical Engineers of Great Britain and the AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS, and the members of the Congress taking part. It is gratifying to find that there is so little dissent from the statements which have been made as to the future of alternating-current traction. Many of you will recall, no doubt, that at one time the electrical profession might have been said to have been divided into two camps, the alternating-current camp and the direct-current camp. The gentleman who preceded me was probably at that time more to be found in the direct-current camp than any other. The other gentlemen who have preceded me were to be found in the alternating-current camp. It is a fact, however, and those who have visited the power stations on the circular tour have noticed that the direct-current men have called in the alternating current to help them out, and combine, therefore, the virtues of the alternating current with the virtues of the direct current.

In the early days the speaker was connected and is still connected, with an organization which had not many prejudices of one kind or another. We had direct current, we had constant current series arc lights, constant-potential direct-current systems, and when the alternating current came we were ready to take that up without prejudice, and find out what there was in it.

In 1886 we put out our original alternating-current apparatus, and finding that the necessity might perhaps arise for motors

on the system, it was at that time the speaker undertook to get a motor for that system, a self-starting alternating-current motor, and the first motor of the repulsion type was made in 1886 and finished in the fall of that year. It was a little affair and was found not to operate very well on the higher frequencies, but by connecting it to a machine, which the speaker was using for electric welding, giving 30 cycles, the speaker found it operated very well and satisfied him as to the general features of the machine. That machine, unfortunately, was sent to an exposition and lost. The Paris Exposition of 1889 had a couple of examples of machines on a little different basis. One of them, the speaker believes, is in England, at the Royal Institution, and another we have at Lynn. It was a machine which was started as a series alternating-current motor, and as soon as it reached a certain speed the commutator was short-circuited and it became an induction motor. It combined, therefore, the elements of both, but the design of such machines in those days was poor. We did not have even the distributed winding; we did not have the arrangements and the proportioning which we have to-day; nevertheless those little motors would give a half horse power for a moderate sized motor on 125 cycles, which was the highest frequency used. The speaker merely mentions these items as matters of history touching on the discussion. They have nothing to do with the discussion as to the different methods and systems of using alternating current in electric railway motors, but the speaker is a strong believer in the field being open for such work. He believes that not only will the direct-current motor maintain its place, but that certain lines of service which the direct-current motor cannot easily take will undoubtedly be taken by the alternating-current motor for railway service, and the exhibition of a system, which you have been able to see in use, and which adapts itself to the use of both currents, is certainly a very instructive one.

PRESIDENT ARNOLD: It occurs to the speaker that he may not have put his explanation in regard to Mr. Lamme's statement in just the way it should be put. The speaker thinks what he meant was that his announcement was the first of a purely single-phase commutator motor system. The speaker thinks with this correction Mr. Lamme will accept his statement. He has not sent the speaker any word, but this additional statement is due him. The speaker thinks his work was first, but Mr. Lamme got in with his announcement in September regarding the single-phase commutator motor.

A paper presented at the 190th Meeting of the American Institute of Electrical Engineers New York, Oct. 28, 1904.

Copyright 1904 by A. I. E. E.

THE TELAUTOGRAPH.

BY JAMES DIXON.

Electrical transmission of handwriting has engaged a certain amount of attention ever since telegraphic transmission of printed characters was successfully carried out.

As early as 1886 Cowper and Robertson brought the writing telegraph[1] into a fairly operative form. This instrument was adapted to operate several receivers in series in "reporting" service, where the regular news ticker service was unobtainable or too expensive. The system was put to some use, chiefly in Pittsburg and vicinity.

The writing was received on a paper tape, advanced at constant speed by clockwork. No pen-lifting device was provided and the words were connected together by a mark of the pen, making figure work poor. As the characters were formed by the combination of the pen motion and the tape motion, a certain amount of practice and skill was required to produce a legible message.

The electrical features were as follows: two independent variable currents were obtained from the transmitter; these passed over lines to the receiver where they traversed two electromagnets set at right angles to each other, and so influenced their effect upon a common armature as to cause the receiver-pen rod to reproduce the motion of the transmitter pencil.

It will be noted that this principle is nearly identical with that of Grühu's Telechipograph,[2] recently described in the technical press, the main differences being that the telechipograph

1. Wm. Maver, Jr., *American Telegraphy.*
2. *Scientific American*, August, 1903.

writes upon a larger field and uses a beam of light, and photographic record instead of a pen with ink record.

Following the writing telegraph, Professor Elisha Gray constructed, at his Chicago laboratory, an instrument which wrote upon stationary paper, and which he called a telautograph. It required four line wires and operated as follows: by means of cords and drums the motions of the transmitting stylus were resolved into two component rotary motions which were used to operate two mechanical interrupters in the primary circuits of two induction coils. The relations of the parts were such that a motion of the transmitting stylus amounting to one-fortieth of an inch caused a complete make-and-break at one or both of the interrupters.

The line currents were the impulses produced in the secondary circuits of the induction coils. These impulses passed over lines to two electromechanical escapements in the receiver. By means of cords and drums their motions were combined and caused to act upon the receiver pen. By the use of relays and condensers and a local battery at each receiver, the paper was advanced when necessary and the pen lifted from and lowered to the paper. The mechanical difficulties met with in perfecting this instrument were very great, and in the apparatus exhibited at the World's Fair in Chicago in 1893 the escapement mechanism was brought to a perfection thought impossible of attainment only a short time before. The writing showed a saw-tooth or step-by-step character due to the action of the escapements. The instrument was abandoned on account of the number of line wires required, limited speed, numerous fine adjustments, and cost and difficulty of manufacture.

In 1893, while still working at the escapement device, Professor Gray patented a variable-current instrument,[1] using two line wires, which worked, in a general way, like the present telautograph. The motions of the transmitter pencil were resolved into two components which were used to vary two line currents, the variable resistances being carbon rods dipping into tubes of mercury. The receiver contained two D'Arsonval movements, to the moving elements of which the pen-arms were attached. Professor Gray never developed this instrument much beyond the laboratory stage, probably on account of his firm belief in the escapement type.

Foster Ritchie, at that time an assistant to Professor Gray,

1. U. S. patent 494,932, April 4, 1903.

gave considerable attention to this patent and perfected an instrument based on it. He obtained a patent for improvements[1] and has produced an instrument that operates in a fairly satisfactory manner[2] under certain favorable conditions.

The telautograph has been brought to its present state chiefly through experimental work done by, or under the personal direction of, Mr. George S. Tiffany, to whom several patents[3] for improvements have been granted. Mr. Tiffany's instrument operates upon the variable-current principle and includes a number of interesting features, among them what may be called a straight-line D'Arsonval movement, which is used to operate the receiver.

The operation may be briefly described thus: at the transmitter a pencil is attached by rods to two lever-arms which carry contact-rollers at their ends. These rollers bear against the surfaces of two current-carrying rheostats, connected to a constant-pressure source of direct current. The writing currents pass from the rheostats to the rollers and from them to the line wires. When the pencil is moved, as in writing, the positions of the rollers upon the rheostats are changed and currents of varying strength go out upon the line wires. At the receiver these currents pass through two vertically movable coils, suspended by springs in magnetic fields, and the coils move up or down according to the strengths of the line currents. The motions of the coils are communicated to levers similar to those at the transmitter, and on these levers is mounted the receiver pen, which, by the motions of the coils, is caused to duplicate the motions of the sending pencil. Fig. 1 shows the circuits of the instrument.

Many of the principles and devices in the instruments are of considerable interest. The method by which the variable currents are obtained is the laboratory arrangement for securing a variable pressure from a direct-current, constant pressure circuit; that is, the line circuit (of constant resistance) is connected as a shunt around that part of the rheostat between the moving roller and the ground or return. Motion of the roller varies the amount of resistance in series with the line and also the amount in parallel with it and fine gradations are easily obtained, giving smooth motion of the receiver pen. In this

1. U. S. Pat. 656,828, Aug. 28, 1900.
2. *Elec. World and Engineer*, Dec. 8, 1900, Vol. XXXVI., No. 23.
3. U. S. patents 668,889 to 668,895 inclusive, Feb. 26, 1901.

way a variable pressure is impressed on the line circuit, giving a variable current. In all the other variable-current instruments, a constant pressure was impressed on line and a resistance in series with the line varied to give the desired variations in current. One result of the shunting method is a better form of rheostat, more easy of construction and handling, in which, also, the heating is better distributed.

The rheostats are wound upon castings of I cross-section, with the turns of wire lying close together on the inner or contact-face. After winding, the insulation on this face is saturated with glue, which is allowed to harden and is then

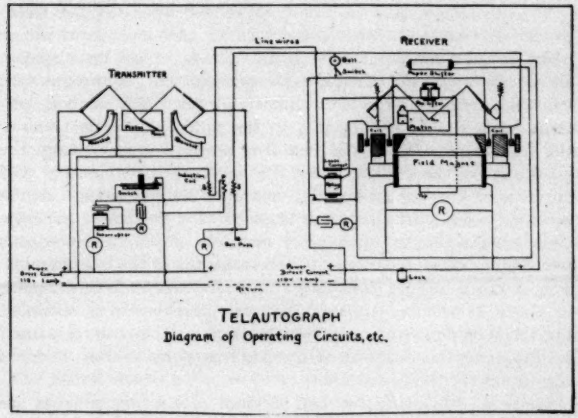


FIG. 1.

scraped off, taking the insulation with it, and giving a surface where contact is possible on every turn of the wire. This gives a rheostat of a large number of small steps, of good mechanical construction, and of low cost.

The receiver operates with what may be called a straight-line d'Arsonval movement. The moving element or coil is wound upon a copper shell for damping effect. The magnetic circuit is so arranged that one pole surrounds the other, forming an annular air-gap of short length and large cross-section in which the direction of the flux is radial. The field is electro-

magnetic and is highly excited, to secure uniformity. The coil, suspended in the annular space, moves up or down with little friction, as it touches the sides of the space of the core very lightly if at all. The principle is the well-known one that a current-carrying coil, in a magnetic field, tends to place itself with respect to the field so that the flux enclosed by the coil shall be a maximum.

The current for operating is taken from the ordinary lighting mains, preferably at about 115 volts. Satisfactory operation has resulted with pressures from 80 up to 250. At 115 volts, receiver and transmitter each require about one ampere while in operation. Fairly steady pressure is necessary as the receiver, being in effect a voltmeter, is rather sensitive to sudden changes, the effect being slight distortion of the message.

A master-switch at the transmitter is provided to do all necessary switching of line and power circuits, to make needed changes in connections and to cut off current when not writing. A relay in one of the lines closes the power circuit of the receiver whenever the transmitter at the distant station is switched on, and serves to prevent waste of current when not in operation.

Attached to the master-switch is a mechanical device which shifts the transmitter paper the space of one line of ordinary writing for each stroke of the switch. The relay mentioned controls the electrical receiver paper shifter and, as each stroke of the switch causes a stroke of the relay, the receiver paper is shifted an amount equal to that at the transmitter. The writing space is about two inches long and five inches wide, allowing for three or four lines of writing. When filled by messages a few strokes of the switch serve to bring fresh paper into position at both receiver and transmitter.

To prevent switching on of the transmitter while its home receiver is receiving a message from the distant station, an electromagnetic lock is connected in the receiver power circuit, controlled by the relay, and locks the home transmitter in the "off" position until the distant transmitter is switched off. If both transmitters were switched on at once neither station would receive any message; the lock is provided to render this condition impossible.

The ink supply is most important and is arranged for as follows: at the left of the receiver platen is a bottle with a hole in the front near the bottom. When filled with ink and tightly corked the ink does not run out of this hole because

of the pressure of the atmosphere. The ink is accessible for the pen at the hole and the surface of ink exposed to evaporation is small.

The pen is made of a piece of german silver bent double, after the manner of a ruling pen, and makes a uniform line in any direction over the paper. It takes up its supply by capillary attraction, from the hole in the front of the bottle. When the receiver is switched off, retractile springs draw the pen-arms to stops so arranged as to bring the pen exactly in front of the hole in the bottle, and when the pen-lifter armature is released the pen is caused to insert its tip in the opening. Thus a fresh filling of ink is obtained each time the paper is shifted. When not in use the pen rests in the ink, always ready to write.

For the prevention of mechanical shocks to the necessarily light moving system of the receiver, it has been necessary to supply means to prevent the switching on or off of the transmitter, and by that action of the receiver, when the transmitter pencil is "out in the field"; that is, at a position other than that corresponding to the opening in the receiver ink-bottle; as in that case the receiver pen would instantly jump to a similar position. This position is called the "unison point," a term having its origin in the days of the "self-propellor" escapement telautograph. By placing a catch, released at only by pressure of the pencil-point upon it, at the transmitter unison point the desired result is accomplished and the transmitter master-switch can not be switched either "off" or "on" unless the pencil be placed at the unison point and held there until the stroke of the switch is completed. In this case, as everywhere, the apparatus is made strong enough to stand any possible shocks, and then every precaution is taken to prevent their occurrence. Aside from shock to the moving system these jumps might shake the ink supply out of the pen and prevent the recording of the message.

The pen-lifter is a magnet placed back of the receiver writing platen, and carrying upon its armature a rod adapted to engage with the pen-arm rods and raise the pen clear of the paper when the magnet is energized. This magnet is controlled from the transmitter as follows: beneath the transmitter platen is a spring-contact, opened by pressure of the pencil upon the paper, and closed by a spring when the pencil is raised. An induction coil having an interrupter in its primary circuit is so

connected to this spring-contact that when the pencil is raised the primary winding is short circuited. The induction coil has two independent secondary windings through which the two variable line currents pass before leaving the transmitter. The effect of the induction coil and its interrupted primary current is to induce in the two line currents superimposed vibrations or "ripples" when the pencil is pressed down on the paper and the spring-contact is open. When the contact is closed, by its spring, and the primary winding is cut out, no vibrations are produced in the line currents. In one of the line wires, at the receiver, is placed a relay upon whose sheet-iron diaphragm armature is mounted a loose contact, consisting of two platinum-silver contacts in series, sealed in a glass tube, to prevent oxidation. A local circuit contains the winding of the pen-lifter magnet and this loose contact.

When the vibrations are present in the line current, due to the pressure of the pencil upon the paper and consequent opening of short circuit of the primary of the induction coil, the diaphragm of the relay is shaken, the loose contact opened and the pen-lifter de-energized, its armature is drawn back by a spring and the pen is allowed to rest against the paper. When there are no vibrations in the line currents due to the raising of the pencil from the paper, the relay diaphragm is at rest and the pen-lifter is energized and the pen is lifted clear of the paper.

The superimposed vibrations used for operating the pen-lifter have another minor effect. The suspended coils, and through them the entire moving system of the receiver, are kept in a state of very slight mechanical vibration while the pen is on the paper. This aids the flow of ink from the pen-point, assists the pen in passing over any roughness or irregularity in the surface of the paper, and materially reduces friction in the joints and pivots of the moving system, and results in better writing. In some of the later instruments the two relays, that for pen-lifting and that for paper-shifting and power switching, are combined in a single piece of apparatus.

For signalling, a push-button is placed upon the transmitter and a call-bell or buzzer is mounted on the receiver. This circuit is disconnected by the master-switch while a message is being written. Spring reels are attached when needed to roll up the received messages for preservation and future reference.

The ordinary arrangements for operation are as follows: the instruments may be operated singly, upon a private line

having an instrument at each end, or on an exchange system where a switchboard provides for connection. Working in this way, satisfactory writing has been obtained with a resistance in each line wire of 1600 ohms and an operating pressure of 110. Multiple operation can be carried out to a limited extent, three receivers being at present the maximum number that can be operated at once, in multiple, using 110 volts. This allows of placing a supervisory machine upon a line.

When no response to messages beyond a bell signal, is required, and the same message is to be sent to a number of stations, a series arrangement of receivers is used. With a transmitting pressure of 110 volts a maximum of seven receivers can be operated from a single pair of transmitting rheostats and rollers. This number may be increased by increasing the pressure or by adding additional rheostats and rollers, operated by the same pencil. Using both these methods a maximum of 50 or more receivers may be operated at once.

Instances in actual commercial use of the arrangements of instruments mentioned are: private lines; the transmission of mail and other orders from office to factory or yards; investigation of checks over lines between paying tellers and bookkeepers in banking concerns, and transmission of messages, usually in cipher, between brokerage firms and cable or telegraph offices. A few moments' thought will bring to mind many places where a telautograph private line could be used to save time and trouble, especially where accurate transmission of figures is essential.

Multiple operation may be resorted to when a third station upon a line desires a record accessible at any time, of what is being sent, as, for instance, when one of the officers of a bank desires to know what passes between his bookkeepers and paying tellers. On such a line the third station receives all messages and can write to either or both of the other stations, should the necessity arise.

Series operation may be used when several stations are to receive the same message and no response except a bell signal is required, as in sending orders in a hotel or club from dining room to kitchen, pantry and wine room; in "reporting" or news service, or for bulletin work, such as the announcement of arrival and departure of trains to a number of stations in a large railway station or freight depot. Fig. 2 shows the standard commercial instrument.

One of the most important uses for series systems has been found in the U. S. Coast Defence Service, in sending ballistic data, such as range and azimuth of target, or character of projectile, from position-finding stations to the gunners. This is called " fire-control communication " and is installed in the forts by the U. S. Signal Corps. In a paper presented by Col. Samuel Reber on " Electricity in the Signal Corps,"[1] will be found a description of the position-finding systems and the desired characteristics of a system of communication for sending this data to the guns are stated as follows: " The system that will successfully solve this problem must be simple in construction, mechanically strong so as not to be affected by the

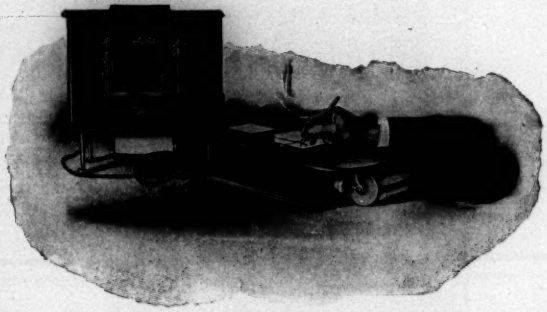


FIG. 2.

blast, as the receivers are placed close to the guns, rapid in operation, and give a character of record that can be read without liability of error." Since that paper was prepared it has been decided that the receivers must be mounted directly on the gun-carriage and can have no shelter other than that afforded by their own cases. Add to these requirements the facts that the instruments must be cared for by post electricians, and operated by enlisted artillerymen, messages must be visible at night; and the operation must be independent of rain, salt mists, cold, heat, or tropical insects, and it is apparent that no easy problem is presented.

A special type of telautograph has been designed for this

1. TRANSACTIONS, A. I. E. E., Vol. XIX., pp. 723 and 724.

service and has been adopted by the U. S. Signal Corps[1] for fire-control communication.

In this "service telautograph" the pen-lifter controlling relay is eliminated and the receiver pen-lifters are operated over a third line wire by the transmitter platen switch directly.

Each gun receiver is enclosed in a water-tight brass case, suspended by springs from the gun carriage directly in front of the gunner. The parts are as far as possible made "brutally

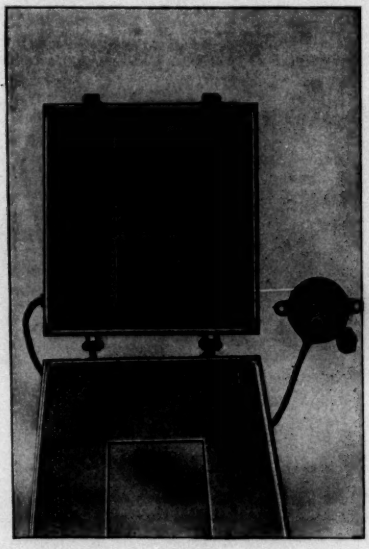


FIG. 3

strong," and the construction is as simple as possible.

The desired rapidity of operation is inherent to the telautograph, and accuracy of record is ensured by careful writing and by the use of a "home" receiver, mounted at the transmitter, where the operator can see it plainly, which is connected in series with the gun receivers and records the messages as actually sent over the line.

1. TRANSACTIONS, A. I. E. E., Vol. XIX., p. 673.

Freezing of ink is prevented by the addition of alcohol; and rain, mists, and insects, as well as the effects of the blast, are shut out by the metal case. A heavy glass window is placed in the case so that messages can be read without opening the case.

A small incandescent lamp inside the case lights automatically when the receiver is writing and may be lighted by pressing a button at other times, thus providing for visibility at night. Fig. 3 shows the army type of receiver mounting.

On warships there is a somewhat similar service to be rendered and the performance of this should fall to the army type of telautograph.

Commercial service has given opportunity for the installation of a considerable number of private line telautographs in actual use, and at least three of each of the other typical installations are in operation at the present time.

Much of the improvement in details of construction and reliability in operation has resulted from experience gained in efforts to perfect the service of these commercial plants. The experience leading up to the special army type of telautograph has extended over a period of about five years and in the present instrument all the requirements, unusually severe as they are, have been successfully fulfilled.

Discussion on "The Telautograph."

F. C. Bates: Possibly Mr. Dixon will give us a practical demonstration of the working of the telautograph.

(Mr. Dixon gave the demonstration.)

C. O. Mailloux: What is the longest distance which has been attained and what are the prospects of longer distances?

James Dixon: The distance is apparently purely a matter of resistance. The highest worked through so far is 1600 ohms in each writing line. The longest line at present in actual operation is seven miles in length, submarine cable, in the service of the U. S. Signal Corps.

The army instruments are of special construction, to permit working out of doors without protection from the weather, hence they are mounted in weather-proof brass cases. The messages must be visible at night and a lamp is therefore placed in the case. This lamp lights when the instrument is in operation.

E. B. Fahnestock: How does a variation in the insulation of a line affect the work?

James Dixon: It affects the shape of the fields to some extent. If it is uniform in both lines it can be compensated for by a line resistance adjuster at the transmitter. In all army work a receiver is mounted before the eyes of the sender and he can see the form in which the message is going to line. If he finds that the field is out of shape he can adjust the line resistance and correct it. In commercial work this difficulty has not yet been met as all the lines in service are of high insulation.

F. C. Bates: Will Mr. Dixon tell us if it is possible to send a message to several different stations at the same time?

James Dixon: The two army series receivers exhibited are part of a set of seven, all of which operate in series and record the same message. Seven receivers can be operated at once by a standard transmitter containing only one pair of rheostats. To operate more than seven receivers, one or more pairs of rheostats and rollers are added, making a double or triple transmitter, in which all the rollers are moved by one pencil. Each pair of rheostats operates seven receivers; that is, a triple transmitter can write to three branches of seven receivers or 21 receivers in all. Multiple operation is possible within certain limits, by using high resistance in the suspended coils and connecting the instruments to the line in multiple. The resistance of copper wire that can be wound on the coils without exceeding a reasonable weight is limited and places a limit on multiple operation.

A. C. Crehore: Is it an error in the paper stating that one ampere is required?

James Dixon: That value is correct. In the transmitter the rheostats each carry about one-quarter of an ampere, the induction coil primary circuit about one-eighth, and each of

the line currents may be as much as two-tenths, making about one ampere which is supplied to the transmitter from the power circuit. In the receiver the field-magnet winding, excited from the power circuit, takes about six-tenths of an ampere, the paper-shifter about one-fourth, and the pen-lifter one-tenth, making a total of about one ampere supplied to the receiver. The line currents are of course variable and range between a maximum of three-tenths and a minimum of nearly zero.

TOWNSEND WOLCOTT: These army instruments were designed especially for the Signal Corps and, as Mr. Dixon has said, one of the principal requirements was that they should be able to withstand the concussion of the guns. There was, at first, some doubt whether the instruments could endure the strain; but so far they have come through unscathed. To be sure, there has been no real warfare in which the telautographs were used, but in the maneuvers at Portland, Maine, a year ago last summer, telautographs were successfully used in a mortar pit, where the suction from the simultaneous discharge of all the mortars was so great that one day it pulled the clapboards off the front of an adjacent building. All this did not prevent the telautographs from working. The ink used to be spattered, in the old type of instruments, but this has been overcome in the present type. The use of the telautograph in the army is to convey information from the range-finder to the guns.

JAMES DIXON: In reference to the effect of shock or concussion from the guns, these particular instruments, (the instruments used in the demonstration), were installed and in use on the battleship Alabama for some time and were subjected to severe tests. One was placed near the trunnions of a 13-inch gun, and about four feet from the gun axis, the gun being trained parallel to the instrument. Repeated shots with full service charges did not develop any faults in the construction or operation of the instrument. These receivers are in the condition in which the test left them, and their operation shows them to be uninjured. The army type springs (indicating springs) have been substituted for the navy suspension springs which are slightly different. In army work an anchorage is to be added to the bottom in the form of a third spring, to prevent the receiver from being pushed out of the vertical position, as for instance, by a person leaning against the case. The question of withstanding the shock is of great importance and the instruments as shown meet all the requirements.

BLANK
PAGE

A paper presented at the 100th Meeting of the American Institute of Electrical Engineers, New York, Oct. 28, 1904.
Copyright 1904, by A. I. E. E.

THE TRANSPOSITION OF ELECTRICAL CONDUCTORS.

BY FRANK F. FOWLE.

The transmission of electromagnetic energy through the ether, by means of conducting wires whose function is that of directing and concentrating the energy flow, is accompanied by mutual interferences between transmission systems which employ in common any considerable portion of the ether. The extent to which the ether is energized, in a direction transverse to the direction of energy flow, is controlled by the design of the transmission circuit and the rate of energy flow. The energy storage-capacity of a transmission circuit is very small in comparison with the transmitted energy, but the great velocity of transmission renders possible the transmission of large energies. The conformations of the electric and the magnetic fields about a line circuit depend, in alternating-current systems, on the number of phases and on the number, size, and separation of the wires. The field at a given point due to a single-phase circuit is constant in direction but variable in intensity, from instant to instant throughout a cycle; the field due to a polyphase circuit varies both in direction and intensity.

Alternating-current transmission systems resolve themselves into two great classes, one for the transmission of power and the other for the transmission of intelligence. Power systems are characterized by: high pressure; large currents; low or moderate frequencies; only one fundamental frequency; relatively great reaction of terminal apparatus compared with line reactions; magnitude of inductive disturbances in the line usually small and important only as affecting regulation; line length less than a wave length, and the flow of energy usually

in a given direction. Telephonic systems are characterized by; low pressure; small currents; high frequencies, variable over a wide range; relatively small reaction of terminal apparatus compared with line reactions; magnitude of inductive disturbances in the line usually large and rarely negligible; line lengths usually greater than the wave lengths and often equal to many wave lengths, and the flow of energy alternating in direction and source.

The general character of the fields set up about the line is the same, whatever the system, and a consideration of

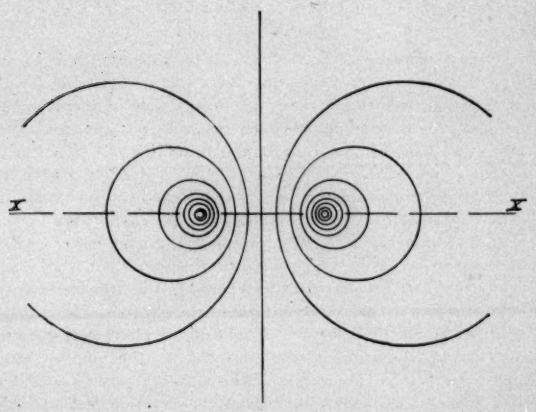


FIG. 1.

this will lead to the theory of transposition. Fig. 1 shows the magnetic field set up about a two-wire circuit; Fig. 2 shows the electric field. These two fields at all points of intersection are at right angles to each other; that is, the electric and the magnetic forces at any given point are perpendicular with respect to each other. Also, the electric pressure is constant in magnitude at all points on any magnetic flux line; or every magnetic flux line is a line of constant electric pressure. The flux density and the intensity of the electric pressure both diminish rapidly as the distance from the wires increases. An instance of this is shown in Fig. 3, which gives, in rectangular

coördinates, the flux density along the X axis of Fig. 1; Fig. 4 shows similarly the electric pressure along the X axis in Fig. 2.

For a single wire having an earth return, the solution above may be applied by considering the surface of the earth coincident with the Y axis· the wire beneath the earth's surface

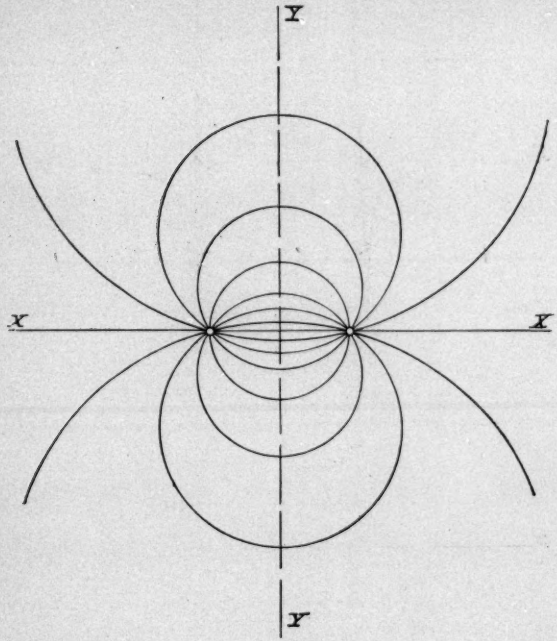


FIG. 2.

will be the electrical image of the real wire above. It will be seen that the fields due to a ground-return circuit in practice extend through a far greater volume of dielectric than in the case of a metallic circuit.

The theory upon which the above curves are based is as follows: Consider a single straight wire in free space, of radius r,

conveying a current I. The work done in carrying a unit magnetic pole circumferentially around the wire, at a radial distance a from it is

$$W = 4\pi I = 2\pi a F \qquad (1)$$

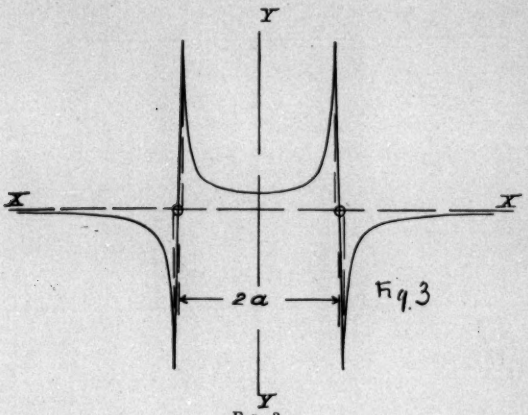


FIG. 3.

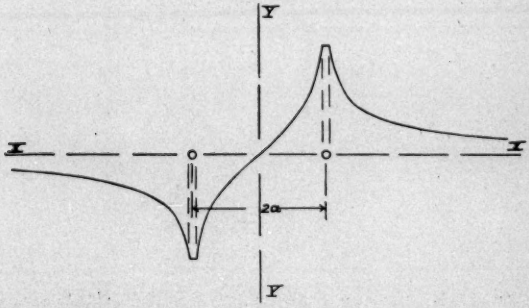


FIG. 4.

where F is the magnetic force at a. The force F acts through the point a perpendicularly to the plane containing the wire and the point a.

Therefore

$$F = \frac{2I}{a} = H \tag{2}$$

where H is the intensity of the magnetic field. In a unit length of wire the total number of flux lines encircling the wire, multiplied by the current is

$$N_1 = \int_r^\infty \frac{2\mu I^2}{x}\, dx \tag{3}$$

where x is the radial distance from the wire and μ the magnetic permeability of the medium.

Assuming a uniform distribution of the current I throughout the cross-section of the wire, we have for the field intensity at a point radially distant b from the centre of the wire,

$$\frac{\pi b^2}{\pi r^2}\left(\frac{2I}{b}\right) = \frac{2Ib}{r^2} \tag{4}$$

and this intensity is due to the current enclosed within the circumference $2\pi b$. The product of the current into the flux, integrated between the limits $b = o$ and $b = r$ is

$$N_2 = \int_o^r \frac{2\mu_1 I^2 x^3}{r^4}\, dx \tag{5}$$

where μ_1 is the magnetic permeability of the wire. The total number of linkages of the flux with the current, multiplied by the current, is

$$N = N_1 + N_2 = \int_o^r \frac{2\mu_1 I^2 x^3}{r^4}\, dx + \int_r^\infty \frac{2\mu I^2}{x}\, dx \tag{6}$$

The inductance* is therefore

$$L = \frac{1}{2}\mu_1 + \int_r^\infty \frac{2\mu}{x}\, dx \tag{7}$$

* This demonstration is due to Jackson; *Alternating Currents and Alternating Current Machinery*, p. 140.

If there is a parallel wire within the field of the first wire, distant r_{12} from it, the portion of the total flux which is linked with it, is

$$M = \int_{r_{12}}^{\infty} \frac{2\mu}{x} dx \tag{8}$$

and this is the mutual inductance of the two circuits.

For a two-wire metallic circuit the inductance will be double the difference between expressions (7) and (8), or

$$L = \mu_1 + 2\int_{r}^{r_{12}} \frac{2\mu}{x} dx$$

$$= \mu_1 + 4\mu \log \frac{r_{12}}{r} \tag{9}$$

For a single wire at height h above the earth, the inductance is

$$L = \frac{1}{2}\mu_1 + 2\mu \log \frac{2h}{r} \tag{10}$$

These expressions in henries per mile are respectively

$$L = \left(0.1609 + 1.482 \log_{10} \frac{d}{r}\right)10^{-3} \tag{11}$$

$$L = \left(0.08047 + 0.7411 \log_{10} \frac{2h}{r}\right)10^{-3} \tag{12}$$

where μ and μ_1 are unity.

The field of force without a two-wire metallic circuit is, from (2)

$$F = 2I\left(\frac{1}{r_{1x}} - \frac{1}{r_{2x}}\right) \tag{13}$$

where the point x is perpendicularly distant r_{1x} from one wire and r_{2x} from the other. From this, the field intensity along the X axis in Fig. 1 is proportional to

$$y = \frac{1}{a+x} + \frac{1}{a-x} \tag{14}$$

for points without the wires and

$$y = \frac{2x}{r^2} \tag{15}$$

for points within the wire. Fig. 3 is plotted from (14) and (15).

Considering the case of two two-wire metallic circuits, as shown in cross-section in Fig. 5,
the expression for their mutual inductance follows at once from expression (8):

$$M = \int_{r_{13}}^{r_{14}} \frac{2\mu}{x}\, dx - \int_{r_{23}}^{r_{24}} \frac{2\mu}{x}\, dx \tag{16}$$

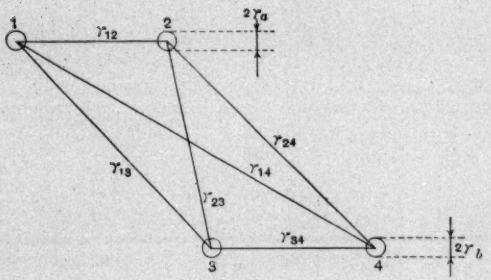


FIG. 5.

$$M = 2\mu \log \frac{r_{14}\, r_{23}}{r_{13}\, r_{24}} \tag{17}$$

In henries per mile this is

$$M = \left(0.7411 \log_{10} \frac{r_{14}\, r_{23}}{r_{13}\, r_{24}} \right) 10^{-3} \tag{18}$$

The foregoing expressions for self and mutual inductance may be established from the standpoint of the kinetic energy of an electromagnetic system, as shown by Maxwell* and Heaviside.†

The introduction of another circuit within the field of a given circuit does not alter the expression for the self-inductance

* Maxwell; vol. II., art. 685.

† Heaviside; Elec. Papers, vol. I., p. 100.

of either circuit. The mutual inductance between the circuits is taken care of in the general equations for the energy of the whole system.

The capacity constants are not quite so simple, because the addition of a circuit within the field of a given circuit changes the constant for the given circuit by itself; and when a third circuit is considered the constants for the two previous circuits are again altered and their mutual constant is also altered and so on, for each circuit added to the group.

Take a system of n conductors with respective charges q_1, q_2, q_3 . . . q_n, and pressures v_1, v_2, v_3 . . . v_n. The pressure of each conductor is a homogeneous linear function of the n charges and the total energy of the system is half the sum of the products of the pressure of each conductor into its charge.

$$\begin{aligned} W = &\tfrac{1}{2} u_{11} q_1^2 + u_{21} q_1 q_2 + u_{31} q_1 q_3 + \ . \ . \ . \\ &+ \tfrac{1}{2} u_{22} q_2^2 + u_{32} q_2 q_3 + \ . \ . \ . \\ &+ \tfrac{1}{2} u_{33} q_3^2 + \ . \ . \ . \end{aligned} \tag{19}$$

Differentiating W with respect to the charge on any conductor we get the pressure of that conductor, for the pressure is the work done in increasing W by adding a unit charge. This gives equations of the form.

$$\left.\begin{aligned} V_1 &= u_{11} q_1 + u_{21} q_2 + u_{31} q_3 + \ . \ . \ . + u_{n1} q_n \\ V_2 &= u_{12} q_1 + u_{22} q_2 + u_{32} q_3 + \ . \ . \ . + u_{n2} q_n \\ &\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \\ V_n &= u_{1n} q_1 + u_{2n} q_2 + u_{3n} q_3 + \ . \ . \ . + u_{nn} q_n \end{aligned}\right\} \tag{20}$$

The coefficient u_{xx} expresses the pressure of the conductor x when its charge is unity and that of all other conductors zero. The coefficient u_{xy} expresses the pressure of the conductor y when the charge on x is unity, the charges on the other conductors being zero, and $u_{xy} = u_{yx}$. Solving (20) for the charges,

$$\left.\begin{aligned} q_1 &= C_{11} V_1 + C_{21} V_2 + C_{31} V_3 + \ . \ . \ + C_{n1} V_n \\ q_2 &= C_{12} V_1 + C_{22} V_2 + C_{32} V_3 + \ . \ . \ + C_{n2} V_n \\ &\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \\ q_n &= C_{1n} V_1 + C_{2n} V_2 + C_{3n} V_3 + \ . \ . \ + C_{nn} V_n \end{aligned}\right\} \tag{21}$$

where C_{xx} is a coefficient of capacity and C_{xy} is a coefficent of induction or mutual capacity. The coefficients C are functions of the coefficients u. Maxwell* shows that the coefficients of pressure are all positive, but none of the coefficients u_{xy} are

* Maxwell; vol. I., chap. III.

greater than u_{xx}; none of the coefficients of induction (mutual capacity) are positive and the sum of all those belonging to one conductor is not numerically greater than the coefficient of capacity of that conductor, the latter being always positive; when there is only one conductor in the field, its coefficient of pressure with respect to itself is the reciprocal of its capacity; if a new conductor is brought into the field, the coefficient of pressure of any other conductor with respect to itself is diminished, the coefficients of capacity are increased and the coefficients of induction (mutual capacity) are diminished. To find the expression for the coefficients u, consider a single wire in free space, with a charge q per unit length.

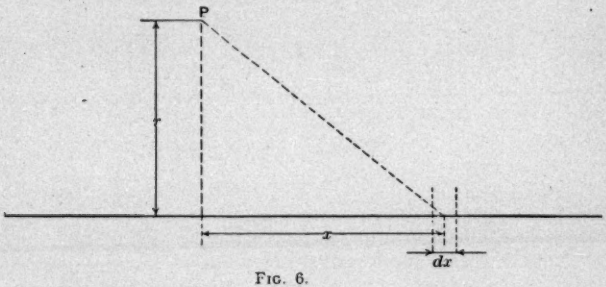


FIG. 6.

The force at P due to the charge $q\,d\,x$ is

$$d\,F_1 = \frac{q\,d\,x}{x^2+r^2} \tag{22}$$

and the force normal to the wire (the longitudinal component vanishes when the whole wire is considered) is

$$d\,F = \frac{q\,r\,d\,x}{(x^2+r^2)^{\frac{3}{2}}} \tag{23}$$

$$F = \int_{-\infty}^{+\infty} \frac{q\,r}{(x^2+r^2)^{\frac{3}{2}}}\,d\,x = \frac{2\,q}{r} \tag{24}$$

But the force is the negative of the partial derivative of the pressure with respect to the distance, or

$$F = -\frac{\delta}{\delta r}(V) \tag{25}$$

whence

$$V = 2q \log \frac{a}{r} \tag{26}$$

a being a constant.

In practice there is always the return conductor of opposite pressure to consider; or if the earth be the return the electrical image must be considered. The pressure at the point P, distant r' from a second parallel wire, with a charge $-q$ per unit length is

$$V' = -2q \log \frac{a'}{r'} \tag{27}$$

The total pressure is

$$V_0 = 2q \log \frac{r'}{r} \tag{28}$$

At an infinite distance r and r' approach unity as a ratio and since $\log 1 = 0$, the constants a and a' must be equal.

Considering a two-wire metallic circuit whose wires have a separation d and radius r,

$$V_1 = 2q \log \frac{d}{r} \tag{29}$$

$$V_2 = -2q \log \frac{d}{r} \tag{30}$$

$$V_1 - V_2 = 2q \log \frac{d^2}{r^2} = 4q \log \frac{d}{r} \tag{31}$$

$$C = \frac{q}{V_1 - V_2} = \frac{1}{4 \log \frac{d}{r}} \tag{32}$$

The pressure coefficient in the above case is

$$u = 2 \log \frac{r'}{r} \tag{33}$$

The pressure of the electric field along the X axis in Fig. 2 is proportional to

$$y = \log \frac{a + x}{a - x} \tag{34}$$

for points without the wires, and is constant within them. The curve in Fig. 4 is plotted from (34).

If the wires are insulated the capacity is slightly increased by the greater specific inductive capacity of the insulation. If the wires are of radius r_1 and the insulating coverings of radius r_2, (32) becomes

$$C = \frac{1}{4 \log \frac{d}{r_2} + \frac{4}{\kappa} \log \frac{r_2}{r_1}} \tag{35}$$

where k is the specific inductive capacity of the insulation. This increase in capacity may amount to several per cent. The above equations are general and apply to a system of any number of wires; a discussion of the subject is given by Heaviside,* with examples worked out for ground-return circuits.

The case of two two-wire metallic circuits in Fig. 5 may be derived as follows:

$$\left.\begin{aligned} v_1 &= u_{11} q_1 + u_{21} q_2 + u_{31} q_3 + u_{41} q_4 \\ v_2 &= u_{12} q_1 + u_{22} q_2 + u_{32} q_3 + u_{42} q_4 \\ v_3 &= u_{13} q_1 + u_{23} q_2 + u_{33} q_3 + u_{43} q_4 \\ v_4 &= u_{14} q_1 + u_{24} q_2 + u_{34} q_3 + u_{44} q_4 \end{aligned}\right\} \tag{36}$$

The circuit conditions are:

$$\left.\begin{aligned} V_1 - V_2 &= V_a \\ V_3 - V_4 &= V_b \\ q_1 + q_2 &= 0 \\ q_3 + q_4 &= 0 \end{aligned}\right\} \tag{36a}$$

A coefficient of the form u_{xy} equals the coefficient u_{yx}. Then we have

$$\left.\begin{aligned} V_a &= (u_{11} - 2\,u_{12} + u_{22})\, q_1 + (u_{13} - u_{14} - u_{23} + u_{24})\, q_3 \\ V_b &= (u_{13} - u_{23} - u_{14} + u_{24})\, q_1 + (u_{33} - 2\,u_{34} + u_{44})\, q_3 \end{aligned}\right\} \tag{37}$$

* Heaviside; Elec. Papers, vol. I., p. 42, p 140; vol II., p 303, p. 329.

But

$$\left.\begin{aligned}(u_{11}-2u_{12}+u_{22}) &= 4\log\frac{r_{12}}{r_a}\\ (u_{33}-2u_{34}+u_{44}) &= 4\log\frac{r_{34}}{r_b}\\ (u_{13}-u_{14}-u_{23}+u_{24}) &= 2\log\frac{r_{14}\,r_{23}}{r_{13}\,r_{24}}\end{aligned}\right\} \tag{38}$$

$$\left.\begin{aligned}q_1 &= C_a V_a + C_{ba} V_b\\ q_3 &= C_{ab} V_a + C_b V_b\end{aligned}\right\} \tag{39}$$

From which it follows that

$$C_a = \frac{4\log\frac{r_{34}}{r_b}}{\left[16\log\frac{r_{12}}{r_a}.\log\frac{r_{34}}{r_b}-\left(2\log\frac{r_{14}\,r_{23}}{r_{13}\,r_{24}}\right)^2\right]} \tag{40}$$

$$C_b = \frac{4\log\frac{r_{12}}{r_a}}{\left[\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\right]} \tag{41}$$

$$-C_{ab} = \frac{2\log\frac{r_{14}\,r_{23}}{r_{13}\,r_{24}}}{\left[16\log\frac{r_{12}}{r_a}.\log\frac{r_{34}}{r_b}-\left(2\log\frac{r_{14}\,r_{23}}{r_{13}\,r_{24}}\right)^2\right]} \tag{42}$$

The above formulas for capacity may be expressed in farads per mile by multiplying by 0.07768×10^{-6}.

The first important conclusion from the expressions for mutual inductance (17) and mutual capacity (42) is that these two constants vanish simultaneously when

$$r_{14}\,r_{23} = r_{13}\,r_{24} \tag{43}$$

Let

$$\frac{r_{23}}{r_{13}} = \frac{r_{24}}{r_{14}} = p \tag{44}$$

Let the coördinates of one circuit be fixed, and be $(+a, o)$ and $(-a, o)$, as in Figs. 3 and 4. If the two wires of the other

circuit are on the locus of the point (x, y), for any particular value of p, (43) will be satisfied. The conversion of (44) to rectangular coördinates is

$$p^2[(x+a)^2+y^2] = [(x-a)^2+y^2] \tag{45}$$

or

$$\left[x+a\frac{p^2+1}{p^2-1}\right]^2 + y^2 = \left(a\frac{p^2+1}{p^2-1}\right)^2 - a^2 \tag{46}$$

This is a system of eccentric circles, there being one circle for each value of p. The plot of this system of circles, from (46), gives the magnetic field of Fig. 1. That is, the mutual

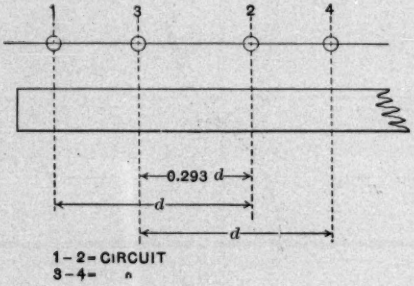


FIG. 7.

interferences vanish when the wires of one circuit are on a single flux line of the field of the other circuit, and therefore enclose none of the magnetic flux of that circuit and are at points of equal electric pressure due to that circuit.

It is seldom in practice that the conditions permit the use of the relations given in (43) and (46). A particular solution is applicable to two two-wire circuits, as independent circuits or as the respective phases of a four-wire, two-phase line. This is shown in Fig. 7.

To show how the constants of mutual inductance and capacity depend on the relative wire positions, the curves in Figs. 8 and 9 have been plotted from

$$\frac{M}{2} = \log\frac{r_{14}\,r_{23}}{r_{13}\,r_{24}} \tag{47}$$

If the circuit 3-4 always maintains a horizontal position, in Fig. 8, and the coördinates of P are (x, y), P being constrained to move in a circle, (47) becomes

$$\frac{M}{2} = \frac{1}{2}\log\frac{[(a+b)^2+c^2]^2-[2(a+b)x]^2}{[(a-b)^2+c^2]-[2(a-b)x]^2} \tag{48}$$

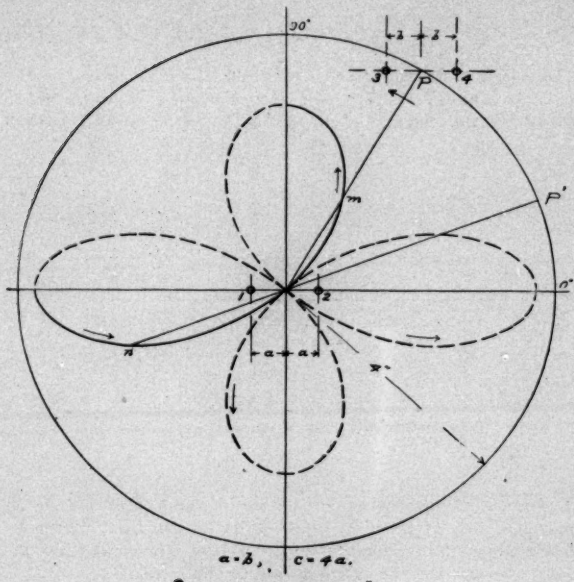


Fig. 8.

where C is given by the locus of P,

$$x^2+y^2 = C^2 \tag{49}$$

If the circuit 3-4 maintains a vertical position, in Fig. 9, and the locus of P is again the circle of equation (49),

$$\frac{M}{2} = \frac{1}{2}\log\frac{(x^2-a^2)^2+(x+a)^2(y+b)^2+(x-a)^2(y-b)^2+(y^2-b^2)^2}{(x^2-a^2)^2+(x-a)^2(y+b)^2+(x+a)^2(y-b)^2+(y^2-b^2)^2} \tag{50}$$

The curves in Figs. 8 and 9 are polar diagrams, giving the relative mutual disturbances as P describes a circle. There are four points in a revolution at which M is zero. It is possible to introduce a third circuit and so locate it that M is zero for any two, and hence for all.

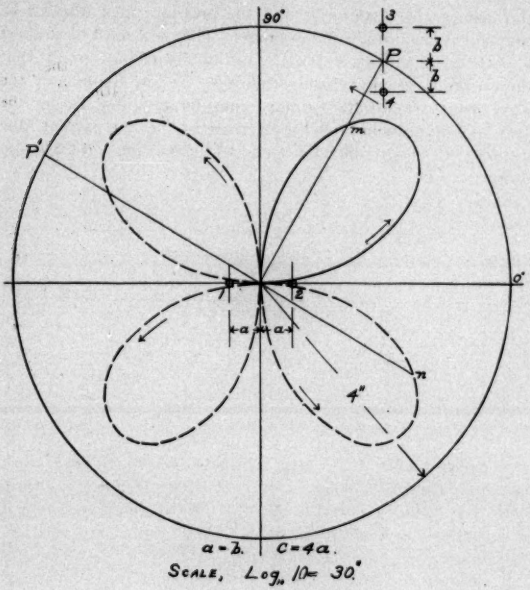


FIG. 9.

When the number exceeds three it becomes, in a practical sense, impossible to prevent mutual interferences. It is evident from expressions (17) and (42) for the mutual inductance and the mutual capacity that the interchange of wires 1 and 2 or wires 3 and 4 will change the signs of these formulas without changing their magnitude. It is evident also that interchanging both wires 1 and 2 and wires 3 and 4 will not alter the formulas in any way; that is the transposition of one of two parallel

circuits will reverse the signs of the mutually induced currents and pressures.

Consider the circuits in Fig. 10.

The additional conditions which are necessary for the disturbances to vanish are as follows. The current in the disturbing circuit must be constant in magnitude and in phase throughout the distance l, and the pressure must likewise be constant in magnitude and in phase. That is, l must be so short a portion of the wave length in the disturbing circuit that these conditions are sensibly fulfilled. At low frequencies the wave length is not the primary consideration, but rather the drop in line pressure and the decrease of the line current, due respectively to wire impedance and to the leakage and the static charge.

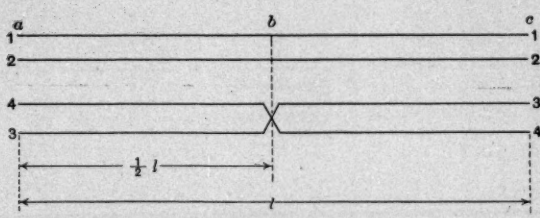


FIG. 10.

As shown by Mr. J. J. Carty, in a paper before the INSTITUTE, on "Inductive Disturbances in Telephone Circuits," in April, 1891, the induced currents due to electric induction cannot be made to vanish entirely, as can those due to magnetic induction.

The treatment of induction between telephone circuits has been by empirical rule rather than theory. It has been determined by experiment, with receivers of a given sensitiveness and transmitters of a given power, how frequently two adjacent circuits should be transposed in order to eliminate the cross-talk. Using two-mile sections, transposed at the centre, the cross-talk is distinguishable with transmission sufficiently powerful for 1000-mile service. Half- or quarter-mile sections, transposed at the centre, are satisfactory; this results in a minimum transposition spacing of one-quarter mile. The existence of cable at each end of the line, in any considerable length, will

reduce the cross-talk. It is necessary to devise different types of transposed circuits, no two transposed alike, in order to treat the cases occurring in practice. The manner of doing this is shown in Fig. 11.

The "exposure," as it is termed, of circuit 1 to circuit 2 is $\frac{1}{4}$; of 1 to 3 is $\frac{1}{4}$; of 2 to 3 is $\frac{1}{2}$; because a transposition at the junction of two sections, each transposed at its centre, has almost no beneficial effect. The exposure of 1 to 5 is $\frac{1}{8}$; of 2 to 6 and 3 to 7, $\frac{1}{8}$; of 2 to 8 and 2 to 9, $\frac{1}{16}$; and so on. The tabulated exposures are given in Fig 12, in terms of the length l of a

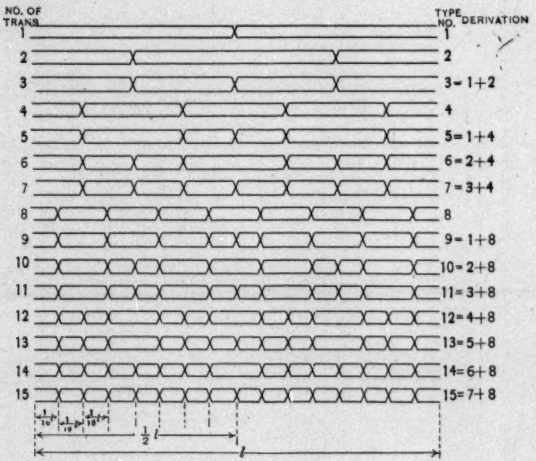


FIG. 11.

transposition section. The derivation of the types is simple; the first three are obvious. The fourth is obtained by doubling the number of divisions of the transposition section from two to four. The fifth is obtained by superposing the first type on the fourth type, the sixth by superposing the second on the fourth, etc. The composition of the complicated types is shown in Fig. 11. So far as the writer is aware this synthetical system of deriving types of dissimilarly transposed circuits is due to Mr. John A. Barrett. The method may be extended as far as desired, but 15 types are usually sufficient.

The choice of a convenient length for l is an important matter. An eight-mile section has been extensively used, but is probably too cumbersome. A much more convenient section would be one four miles in length.

If there are only a few circuits, a two-mile section may be

	Exposure of Type No.													
To	1	2	3	4	5	6	7	8	9	10	11	12	13	14
2	$\frac{1}{4}$													
3	$\frac{1}{4}$	$\frac{1}{2}$												
4	$\frac{1}{8}$	$\frac{1}{8}$	$\frac{1}{8}$											
5	$\frac{1}{8}$	$\frac{1}{8}$	$\frac{1}{8}$	$\frac{1}{2}$										
6	$\frac{1}{8}$	$\frac{1}{8}$	$\frac{1}{8}$	$\frac{1}{4}$	$\frac{1}{4}$									
7	$\frac{1}{8}$	$\frac{1}{8}$	$\frac{1}{8}$	$\frac{1}{4}$	$\frac{1}{4}$	$\frac{1}{2}$								
8	$\frac{1}{16}$	$\frac{1}{16}$	$\frac{1}{16}$	$\frac{1}{16}$	$\frac{1}{16}$	$\frac{1}{16}$	$\frac{1}{16}$							
9	$\frac{1}{16}$	$\frac{1}{16}$	$\frac{1}{16}$	$\frac{1}{16}$	$\frac{1}{16}$	$\frac{1}{16}$	$\frac{1}{16}$	$\frac{1}{2}$						
10	$\frac{1}{16}$	$\frac{1}{16}$	$\frac{1}{16}$	$\frac{1}{16}$	$\frac{1}{16}$	$\frac{1}{16}$	$\frac{1}{16}$	$\frac{1}{4}$	$\frac{1}{4}$					
11	$\frac{1}{16}$	$\frac{1}{16}$	$\frac{1}{16}$	$\frac{1}{16}$	$\frac{1}{16}$	$\frac{1}{16}$	$\frac{1}{16}$	$\frac{1}{4}$	$\frac{1}{4}$	$\frac{1}{2}$				
12	$\frac{1}{16}$	$\frac{1}{16}$	$\frac{1}{16}$	$\frac{1}{16}$	$\frac{1}{16}$	$\frac{1}{16}$	$\frac{1}{16}$	$\frac{1}{8}$	$\frac{1}{8}$	$\frac{1}{8}$	$\frac{1}{8}$			
13	$\frac{1}{16}$	$\frac{1}{16}$	$\frac{1}{16}$	$\frac{1}{16}$	$\frac{1}{16}$	$\frac{1}{16}$	$\frac{1}{16}$	$\frac{1}{8}$	$\frac{1}{8}$	$\frac{1}{8}$	$\frac{1}{8}$	$\frac{1}{2}$		
14	$\frac{1}{16}$	$\frac{1}{16}$	$\frac{1}{16}$	$\frac{1}{16}$	$\frac{1}{16}$	$\frac{1}{16}$	$\frac{1}{16}$	$\frac{1}{8}$	$\frac{1}{8}$	$\frac{1}{8}$	$\frac{1}{8}$	$\frac{1}{4}$	$\frac{1}{4}$	
15	$\frac{1}{16}$	$\frac{1}{16}$	$\frac{1}{16}$	$\frac{1}{16}$	$\frac{1}{16}$	$\frac{1}{16}$	$\frac{1}{16}$	$\frac{1}{8}$	$\frac{1}{8}$	$\frac{1}{8}$	$\frac{1}{8}$	$\frac{1}{4}$	$\frac{1}{4}$	$\frac{1}{2}$

Fig. 12.

used. A case of this sort is a ten-wire line, on a single-cross-arm, as shown in Fig. 13.

The following table gives the theoretically permissible exposure between any two circuits. The basis on which this table is computed is as follows; calculate $\frac{M}{2}$ from (47) for

each combination of two circuits; if the standard of exposure between two adjacent circuits is, say, one-fourth of a mile, then the exposure between any other two circuits will be inversely proportional to the calculated $\frac{M}{2}$ for the two latter circuits.

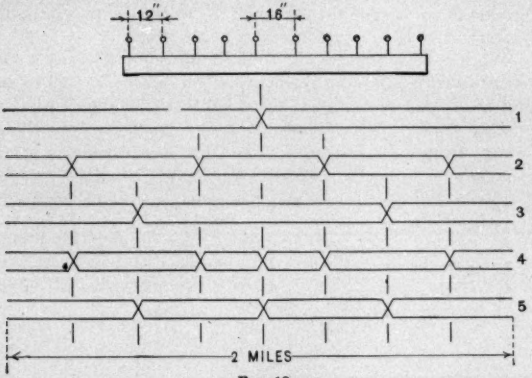


FIG. 13.

To	Circuit No.				
	1	2	3	4	5
1					
2	0.25				
3	0.90	0.21			
4	2.85	1.31	0.21		
5	4.95	2.85	0.90	0.25	

The tabular values are in miles.*

* See *Electrical World and Engineer* for Nov. 21, 1903, an article by the author on this subject, from which the table is taken.

The procedure in applying the sections to a long line is as follows: beginning at the first pole, of the open-wire line, apply the sections consecutively until the last section is approached. It is seldom the line length is a multiple of the section length, so the remainder should be a special section by itself, if over half the length of a standard section, or should be added to the last section, making a special section longer than the standard. The distances between transposition poles will be shortened or lengthened sufficiently to apply the standard section.

When there are several cross-arms it will simplify the construction if the transposition types are so chosen, in laying out a standard section, that there will be as few different types of transposition poles as possible. The junction of two lines which separate, or become joint, is a point which should be made

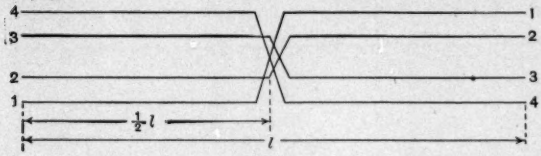


FIG. 14.

the junction of the transposition sections, as well. The 15 types shown in Fig. 11 will be sufficient for a 40-wire line, because there will be certain diagonal exposures requiring transposition only at long intervals, and these extra transpositions may be located at the junction poles between sections.

Single-wire grounded lines cannot be transposed, and for this reason are not extensively used. They may be operated for short lengths of a mile or so, without interference from cross-talk, if very low-power receivers are used. For greater lengths, there will be serious cross-talk; the low-power receiver is still necessary to remove extraneous inductive disturbances.

Phantom circuits, built up from metallic circuits, are not in extensive use. The ordinary transposition is of no effect, and unless specially transposed such circuits will cross-talk and will be subject to extraneous induction. The transposition of a phantom may be done in several ways. Fig. 14 shows a transposition in which the phantom is transposed, and its two com-

ponent circuits, while not transposed with respect to each other, are transposed with respect to any other parallel circuits but are also moved in position, thereby partly offsetting the latter transposition.

A second method is shown in Fig. 15, where the two component circuits are not transposed with respect to each other, or to any additional parallel circuits.

Another method, in which the component circuits are transposed with respect to each other, is shown in Fig. 16.

If the regular transposition sections are not too long, the

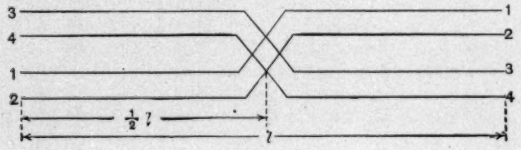


FIG. 15.

phantom transposition may be placed at a pole forming the junction between two sections, where it will have no effect on the regular sectional system. If it is placed within a section it will upset the tabular exposures shown in Fig. 12. If many phantoms are employed, it will be best to lay out a section with only the phantom transpositions and then to superpose

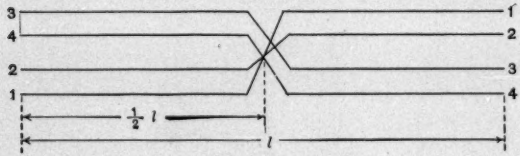


FIG. 16.

on it the additional simple transpositions to eliminate the cross-talk between the metallic circuits themselves.

When telephone lines are paralleled by power lines the transposition problem becomes more complicated. It is necessary to recognize the manner in which the disturbing circuits alter the magnitude of their influence, by reason of abrupt changes in line pressure or line current, and changes in the wire spacings. If circuit 1-2, in Fig. 10, is the power circuit and 3-4 is the telephone circuit, there will be no mutual interferences if the

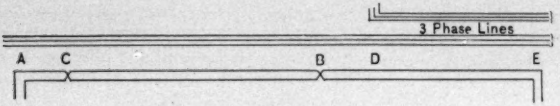
distance l is not great. That is, the percentage pressure drop in 1-2 must be small enough so that the total induced charges on the portion $a\,b$ are sensibly equal and opposite to those on $b\,c$; likewise, the percentage current loss in 1-2 must be so small that the magnetically induced pressure in the portion $a\,b$ is equal and opposite to that in $b\,c$. The question as to whether electric or magnetic induction is the greatest is complicated by the radical differences between the systems. In long telephone lines the electric induction may predominate; the impedance of an indefinitely long line is usually several hundred or a thousand ohms, and therefore the pressure is very much greater in magnitude than the current. In power circuits this ratio is dependent largely on the load, in any given case, but there are many instances where the ratio of pressure to current is small. The magnetic induction is usually predominant to a large degree, in the latter cases. There have been instances of exposure to circuits giving 24-hour service, from which the induction was heavy only during the period of load.

If the circuit 1-2, in Fig. 10, has connected to it a transformer or a branch circuit within $a\,c$, the effect of the transposition is no longer to neutralize the induction. If the transformer is at b the transposition will have the least effect. If 1-2 is a constant-current circuit and an arc lamp is cut in, the effect will be the same, as regards the efficiency of the transposition. A change in the spacing of the wires 1-2 will also decrease the effect of the transposition.

Therefore that portion of the disturbing line within which the conditions, affecting the phase or the magnitude of the induced currents and pressures, are constant should be treated as a section and all the telephone circuits should be transposed opposite its centre. The regular cross-talk transpositions should be removed from the section. If the total external exposure to the power line involves several consecutive sections, the cross-talk transpositions should be opposite the junction of two sections, at the point where the disturbing current and pressure change in magnitude or phase.

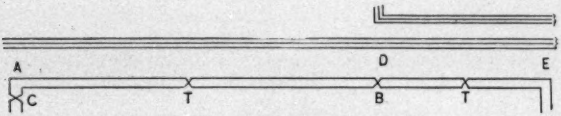
An illustration of this is shown in Fig. 17 and 18, which shows the case in which the writer first tried this method, in 1902, on a telephone line paralleling two three-phase circuits. Fig. 17 shows the initial situation, which caused service complaints. Fig. 18 shows the remedy, which eliminated the interferences entirely.

A more general case is shown in Fig. 19; this is hypothetical but illustrates various conditions. This method works well until the character of the exposure becomes complicated, and then the transpositions become so frequent as to be imprac-



B and C are cross-talk transpositions, ½ mile apart.
Only one telephone circuit is shown for simplicity.

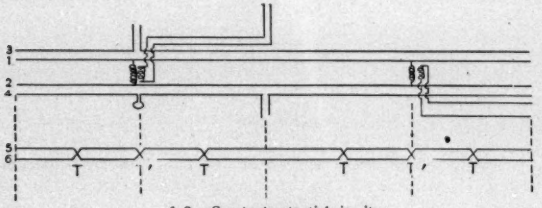
FIG. 17.



All telephone circuits are transposed at T.

FIG. 18.

ticable and, further, they frequently cannot be properly situated because of physical limitations. If the electric light and power system is developing rapidly the exposures are changed frequently by new construction. Again the telephone line may



1–2 = Constant potential circuit.
3–4 = Constant current circuit.
5–6 = Telephone circuit.
T = Induction transpositions.
T′ = Cross-talk transpositions.

FIG. 19.

be separated from the power line by the width of a street; here the induction, while not excessive, is yet troublesome; and the theoretical transposition system to meet the conditions of ex-

posure is just as elaborate as though one line were beneath the other. Twisted pairs or cable will meet this condition, although either remedy impairs the telephonic line efficiency. A prior consideration is whether the power wires are not separated, with respect to each other, farther than is necessary with the pressure employed and whether the separations are uniform. Fig. 20 shows a case in point, where the change in the separation of the wires *a b* from several feet to less than two feet so reduces the field of the power circuit that the cross-talk transpositions in the telephone line practically take care of the induction.

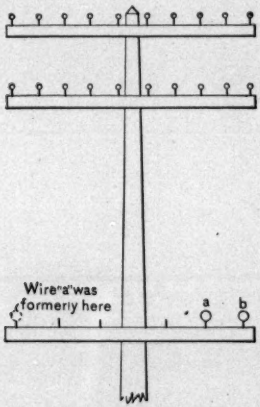


FIG. 20.

Where telephone lines have paralleled transmission lines along highways, separated by 15 or 20 feet, or by the width of the highway, the following practice has been employed. All the telephone circuits are transposed at every tenth pole—40 poles per mile—the cross-talk transpositions occurring midway, so that transposition poles are five spans apart, the cross-talk and the induction transposition poles alternating. This practice, while it is somewhat uncertain of producing the best results, is probably best suited to certain requirements,—where the method of sections would not produce any better results because of the physical unevenness and crookedness of the right-of-way.

Not infrequently high-pressure systems are transposed for their internal protection. When telephone circuits are on such pole lines, the transpositions in the power circuit may be availed of to reduce induction in the telephone circuits, but in the case of separate telephone circuits, on a parallel pole line of separate ownership, it seems wiser to treat such transpositions as neutral points—to be opposite the junction of two transposition sections of the telephone line. The question of where to locate telephone wires on high-pressure lines and how to protect them contains material for a paper by itself. In general the induction from a three-phase line is slightly greater than from a single-phase line having the same wire spacing and current per wire and a pressure equal to the Δ pressure. The separation between the wires should be as small as consistent with the length of span and their plane suitably arranged with respect to the plane or planes of the power circuits.

FIG. 21.

A three-wire, three-phase line will have two transpositions within a section, as in Fig. 21; two complete sections are shown.

It seems to be fairly general practice to transpose high-pressure systems, but it has been the writer's observation that the length of a section, l in Fig. 21, is usually three miles at least. On that account it is difficult to avail of the power line transpositions in transposing the telephone line, and it is usually necessary to treat them as the junction points between adjacent sections.

On account of the very low frequency and the high ratio of pressure to current customary in high-pressure practice, there are usually no inductive interferences if the power and the telephone lines are separated by the width of a highway or 30 to 40 feet, because the regular cross-talk transpositions are sufficient.

In the case of a single telephone circuit paralleling a power circuit, the frequency of transpositions is a problem requiring calculation in any given case, because of the lack of standard

practice in regard to wire spacing and circuit location. The writer made a series of listening tests with a bipolar receiver of 70 ohms resistance to determine the permissible current at low frequencies which would not interfere with telephonic transmission over the longest lines—1000 miles and upwards. The circuit is shown in Fig. 22.

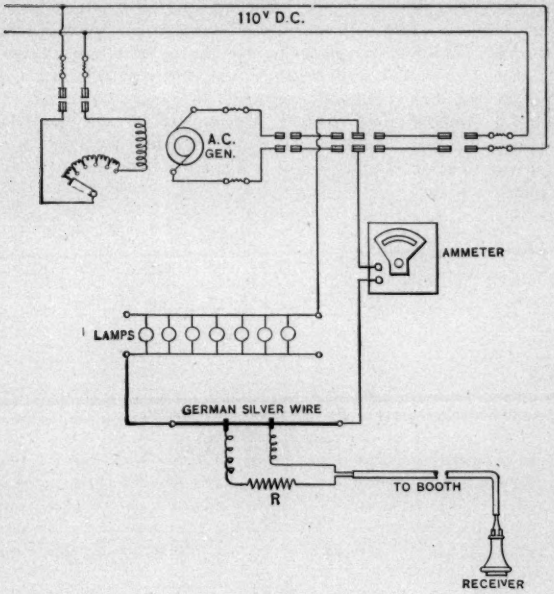


FIG. 22.

The method was that of deriving a very small known pressure from a non-inductive resistance and inserting a very large non-inductive resistance R (1000 to 20 000 ohms) in series with the shunt circuit containing the receiver. The listening tests were made by four observers, who adjusted R to the minimum permissible value, in their estimation. The average results are plotted in Fig. 23.

Naturally these results, based on ear measurements, are not highly precise, but they represent very small disturbances and are safe practice. In the case of short telephone circuits on power lines, used for private purposes, the receiver power may be much reduced and the permissible terminal current greatly increased. The method is shown in Fig. 24; the condenser is not wholly essential, but it increases the selective action.

The general theory of mutual disturbances in parallel cir-

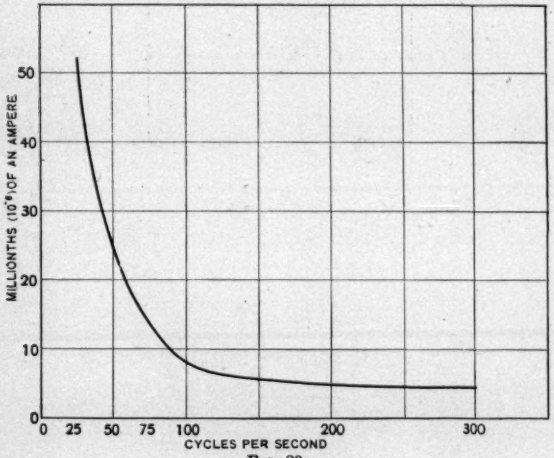


FIG. 23.

cuits, in complete form, is too elaborate to introduce here. It may be found in Vol. I. of Heaviside's Electrical Papers.*

The question of leakage is a consideration prior to that of transposition, for the theory of transposition rests on the hypothesis of electrically balanced circuits. The ordinary pony glass insulator seems to be sufficient where there are no high pressures on the same pole line. In cases of joint lines and of telephone circuits on high-pressure lines additional insulation, in the way of heavier insulators, often seems to be necessary. An elabo-

*Electrical Papers, vol. I, on "Induction Between Parallel Wires."

rate discussion of what constitutes good insulation is not in place here, but the best construction in this respect is the first essential to successful transposition.

There are two types of construction in use, in making trans-

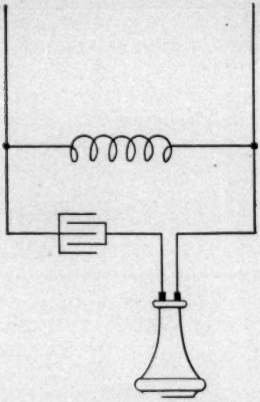


FIG. 24.

positions. One of these, the old-fashioned square transposition made by dead-ending both wires, each way, on two-piece insulators, and cross-connecting, is familiar to all. The other method is shown in Fig. 25; it requires two spans in which to

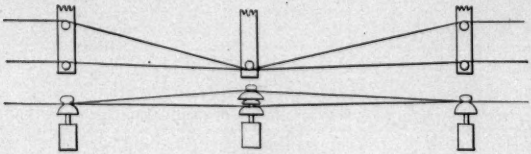


FIG. 25.

complete the entire transposition. It is known as the "Murphy" and the "single-pin" transposition, and is coming into general use.

It has the comparative advantages of less first cost and

simpler construction. It can be cut in at any time, cut out, or moved several poles, at less cost and with much less work than in the case of a square transposition. If transpositions occur frequently, every $\frac{1}{2}$ or $\frac{1}{4}$ mile, the line capacity is increased a few per cent. and the line inductance diminished, with a consequent slight increase in attenuation. The square transposition has the advantage of concentrating the entire transposition within a very short length and of not altering the plane or the separation of the wires. While the single-pin transposition changes the plane of the circuit, the wire separation is greatly reduced and this is an advantage. Since it requires two spans in which to make this transposition, it is possible to transpose only at every other pole, as a maximum, in case of excessive induction, against every pole for the square transposition. For regular cross-talk transpositions the single-pin type is now preferred.

In conclusion, it seems evident that the recommendation of standards, in the matter of wire separations, standard cross-arms, and standard systems of transposition, would greatly facilitate the removal of inductive interferences and materially assist the builders of telephone circuits throughout the country. This matter is suggested for the consideration of the INSTITUTE.

Discussion on "The Transposition of Electrical Conductors."

W. S. Franklin: The speaker's objection to these established methods is that in both cases the fundamental equations are based upon ideal conditions; which even as ideal conditions are impossible and meaningless. Precisely the place where the mathematics is hitched on to the physics, there is no physics at all, nothing in fact but an unconstrained fiction. Now, the speaker knows of no case in which physically significant mathematics cannot be established on the basis of real conditions. It is physically meaningless to consider a long straight wire as a circuit, and the idea of inductance of such a wire is absurd. It is also physically meaningless, in all strictness, to consider a lone electrical charge; and the capacity of an isolated sphere, so universally discussed in treatises on physics, is very nice and simple, but the student who is drilled in that idea never can quite understand a condenser. The real ideas are inductance of *circuits*, capacities of *condensers*; that is, of two bodies in the simplest cases, and mutual inductance of circuits and coefficients of mutual capacity of condensers. Of course, the speaker does not mean to say that Maxwell's theory of a system of charged bodies is essentially wrong, but he does mean to say that it is not as intelligible, not as thinkable, if you please, as it would be if it did not involve the highly fictitious idea of the electrical pressure coefficient of a body with respect to itself. and of the capacity coefficient of a body with respect to itself, The speaker cannot think of such a thing, and he is sure that a careful analysis of the ideas of anyone who thinks he thinks of the pressure coefficient of a body with respect to itself or of the capacity of a sphere, would reveal the fact that the ideas of that person really refer to mathematical expressions or to words, not to physical things at all.

Mr. Fowle says that cable ends on a long telephone line serve to reduce cross-talk, to increase the effectiveness of the transposition on the middle portions of the line. Does he mean to say that it is because of the attenuation which takes place in the cable ends? or because of the very complete transposition which is accomplished in a twisted cable?

F. F. Fowle: The decrease in cross-talk, which occurs when there is a terminal cable, is due, in the opinion of the speaker, to the attenuation in the cable, which diminishes the power of the cross-talk currents coming from the distant open-wire line.

W. J. Lansley: What does Mr. Fowle regard as the permissible distance, the ordinary minimum distance between telephone circuits and single phase 2000 volt power circuits?

F. F. Fowle: Does Mr. Lansley mean from the standpoint of the hazard to the circuit or the standpoint of induction?

W. J. Lansley: Standpoint of induction.

F. F. Fowle: It depends not only on the pressure of the circuit, but on the load and on the distance between the wires of the power circuit and the distance between the wires of the

telephone circuit. In the opinion of the speaker it is not possible to answer Mr. Lansley's question generally. Perhaps a specific case could be answered approximately.

W. J. LANSLEY: Take the pin distance between the wire. Suppose the 2000 volt wires are eight inches apart, and your telephone wires are the same distance apart, how far away should the telephone wire be from the power wire, presumably on the same pole line?

F. F. FOWLE: The speaker's opinion, in this case, is that the circuits should be separated at least two or three feet and that the telephone circuit should be transposed every ten poles, or every quarter mile. The size of the wires, the load on the alternating current circuit and the frequency are factors in determining the distance between transpositions. If the two circuits are on the same cross-arm, there is likely to be more leakage than there would be if they were on separate cross-arms. The use of extra heavy insulators on the telephone circuit is advisable.

W. S. FRANKLIN: The speaker understands the difficulty from leakage is partly balanced by transposition. Mr. Fowle do you depend on transposition at all for obviating bad insulation? Do you find it practicable?

F. F. FOWLE: The speaker is not aware that transpositions have been depended on in such cases. In telephone work it is essential to make frequent insulation tests; the insulation should be the same between each wire and earth and should be high. The speaker recalls an insulation measurement on a line nearly 1000 miles long which gave between 40 and 50 megohms per mile, on a dry, clear, cold day. An insulation resistance of 50 megohms per mile in good weather indicates first class construction, with the pony glass in ordinary use. In wet weather the insulation may fall to one megohm per mile, or less; but at one megohm per mile the attenuation is not increased to a noticeable extent and the distortion is diminished.

F. F. FOWLE (*by letter*): Certain of Professor Franklin's remarks do not seem to the writer to be fully justified.

The connection between the physical and the mathematical sides of any question is seldom obvious, in the step by step development, without careful study. This study is obviously the occupation of the student, but the engineer is after results by the shortest paths; and his education and experience enable him to conduct his researches without a too laborious attention to the physical interpretation of each step. The object of the mathematical investigation of inductance and capacity of aerial wires is obvious in Figs. 1 to 4, 8, and 9, and in the application of its results to the choice of types from Fig. 11 in treating a real situation, as exemplified in Fig. 13.

The writer has never seen elsewhere the deduction of equations (40), (41), and (42). The fact that the investigation is an extension of Heaviside's method and is based on Maxwell's fundamental equations, seems an advantage rather than otherwise. If the results are inaccurate or if there are more rational modern methods the writer will gladly learn of it.

BLANK
PAGE

A paper presented at the 191st Meeting of the American Institute of Electrical Engineers, New York, November 25, 1904.
Copyright 1904, by A. I. E. E.

PROBLEMS OF HEAVY ELECTRIC TRACTION.

BY O. S. LYFORD, JR., AND W. N. SMITH.

A study of the general subject of electric traction for the suburban lines of present steam roads discloses some interesting features which do not necessarily arise as important factors in the selection of equipment for rapid transit lines in cities or the usual interurban lines. Furthermore, the many variables that enter into the problem lead to a serious question as to the necessity of the elaborate methods of determining train and motor characteristics which have been put forth in the recent literature on heavy electric traction. The advantage of simpler and shorter methods becomes very apparent.

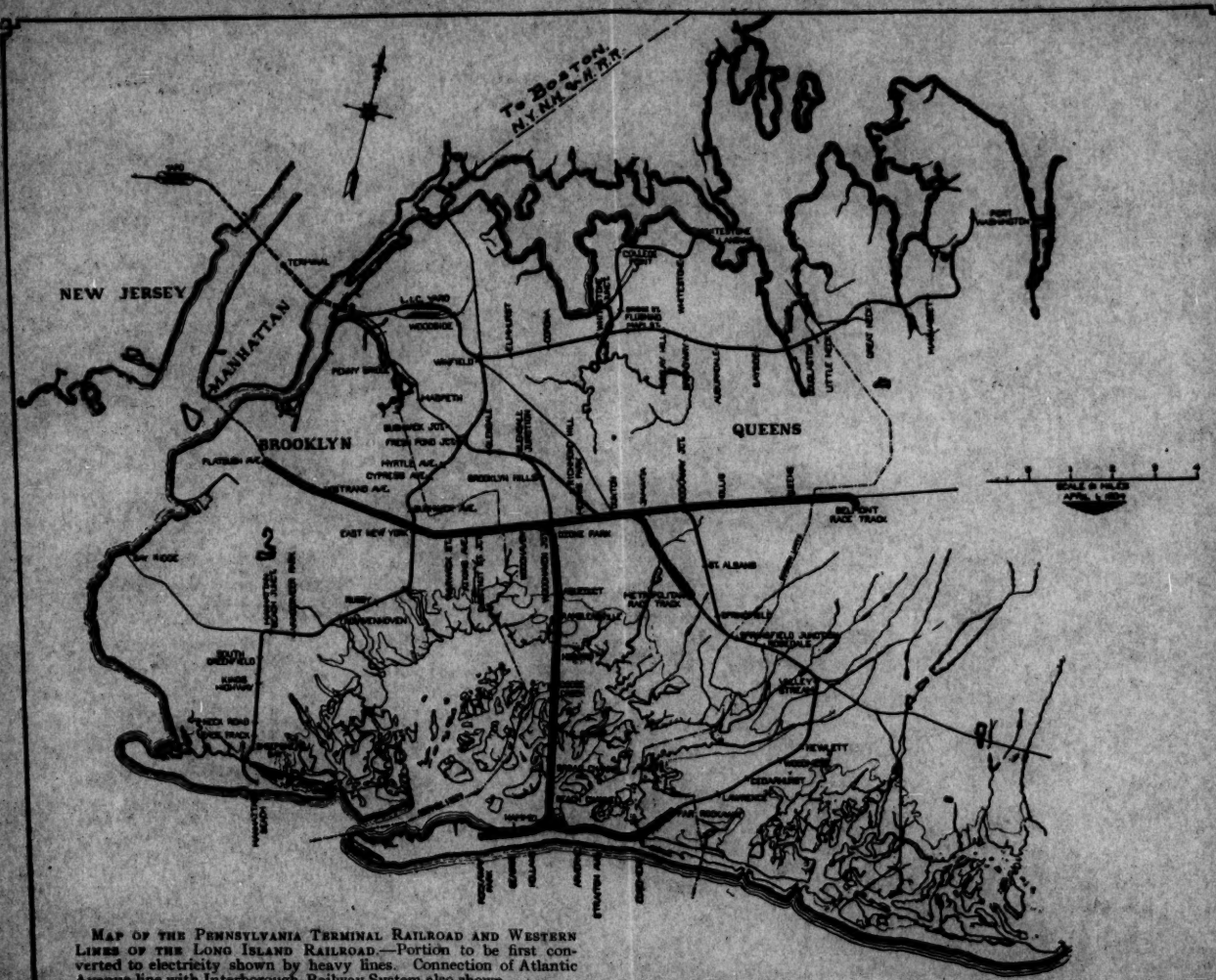
Work now in progress for the Long Island Railroad Company may be taken as typical of projects of this character. It is the purpose of this paper to place before the INSTITUTE some of the questions brought out in the engineering of this work and to describe more particularly some of the simple things that were done to facilitate decision regarding motor equipments for cars.

The Long Island Railroad system has at present two passenger terminals in the City of New York, one at Atlantic Avenue and Flatbush Avenue in the Borough of Brooklyn and one at the Thirty-fourth Street Ferry in Long Island City, Borough of Queens. When the tunnels of the Pennsylvania, New York, and Long Island Railroad Company are completed there will be a third terminal for the Long Island Railroad passenger traffic in the Borough of Manhattan. From the present terminals there branches out an extensive system of through and suburban lines, over which is maintained a train service, both express and local, reaching all parts of the Island. In addition

to the suburban service into these terminals there is an interchange of traffic with the Brooklyn Rapid Transit Company at two points, and a connection is to be established between the subway system of the Long Island Railroad in Atlantic Avenue and the extension of the Rapid Transit Subway now being constructed between Brooklyn and the south end of Manhattan. The accompanying map shows the location of the western lines of the Long Island Railroad and the new connections which are to be made.

Extensive plans for the electrification of the suburban service of this road have been under consideration for some years. These plans provide for the immediate adoption of electric traction on the lines emanating from Flatbush Avenue and for a progressive extension of electric traction over all of the strictly suburban routes, as rapidly as the conditions shall justify. On some of these routes the traffic is of a purely suburban nature, providing facilities for out-of-town residents to reach Manhattan and Brooklyn. On other sections the important traffic is an excursion movement to and from New York's great playgrounds at the beaches. For the convenience of the suburban residents, a frequent service in comparatively short trains is to be provided, but for the excursion service comparatively long trains are necessary. As a result, the number of cars per train in this system will vary from one to eight or possibly ten. The initial service, limited to a maximum of six cars per train, results in 52 types of runs varying in number of cars per train and distance between stops. On some sections the lines are fairly free from grades and curves, but on others the grades and curves are heavier than would be supposed from a general knowledge of the contour of Long Island. These few statements will indicate in a general way the complex nature of the problem involved in the selection of a suitable electrical system for such a service and in the determination of types and sizes of apparatus to be used. In the working out of large enterprises important details are frequently settled by quite simple processes of reasoning. Even in a complex problem like the one under consideration, some main points may be decided in this way.

(a) The number of cars per train varies from one to six, as stated. Eight- or ten-car trains may be desirable at times. Such variations in train length cannot be provided for economically with electrical locomotives. Motor-cars must, therefore, be used, and for all except trains of one or two cars, more than



MAP OF THE PENNSYLVANIA TERMINAL RAILROAD AND WESTERN LINES OF THE LONG ISLAND RAILROAD.—Portion to be first converted to electricity shown by heavy lines. Connection of Atlantic Avenue line with Interborough Railway System also shown.

one motor car per train is necessary. The multiple-unit system of motor-car operation is, therefore, best suited to this service.

(b) The greatest flexibility for make-up of trains is obtained by making all cars motor-cars.

(c) On the other hand the first cost of equipment and the cost of maintenance and inspection is least if the motor selected is of the largest size practicable, and the number of equipments required is thus made a minimum.

(d) For a miscellaneous service of the character contemplated all trains, both local and express, should preferably be provided with equipment having the same speed characteristics, so that all motor cars are available for all classes of service. (Trains may operate as express in one direction and as local in the other.)

(e) For express runs of this suburban service, averaging not over five miles between stops, a moderately high speed, say 50 to 55 miles per hour, is found by experience in steam practice to be most suitable. For these runs, therefore, it is essential that the electric trains shall be able to approximate these speeds.

(f) Future development of the service, such as increase in number of stops and decrease in running time, will mean heavier work for the motors. Therefore, reasonable reserve must be provided in the equipment, and consideration must be given to equipment which will make possible a convenient increase in number of motors per train.

Size of Motors:

The largest motor in general use for motor-car trains is of 200 h.p. nominal rating, two of these being about the limit of motor capacity that can be placed on a truck with 33- or 36-inch wheels and a reasonably short wheel-base. On the basis of condition (c), this should be the motor adopted, provided the train combinations can be effected satisfactorily with motors of this size. Condition (f) is also complied with by selecting the largest motor practicable, as the number of motors per train in the initial service will then be a minimum.

Gear Ratio:

To meet condition (e), a gear ratio must be selected which permits the operation of trains at high speeds without damage to the equipment. On the other hand, the best starting conditions and least heating effect are obtained with high gear

ratio. The gear ratio should, therefore, be as high as practicable and still permit of the maximum train speeds necessary for the express schedules. Provision must also be made for extra speeds which may occur on down grades. From observation of the existing service it was concluded that it is safe to assume 60 miles per hour as a maximum.

TRAIN WEIGHTS:

The motor cars of the service are to be new steel cars similar to those adopted for the Rapid Transit Subway. For the determination of motor characteristics, trailer cars were assumed to have the same size and weight of bodies. The weights assumed were as follows:

	Motor Car.	Trailer.
Seated Load	81 000 lb.	60 400 lb.
Standing Load	88 000 lb.	66 000 lb.

These assumed weights are in practical agreement with the actual weights of the subway equipment

The 200-h.p. motor was found to be the proper size for the service of the subway; but the schedule conditions are so different that this in itself does not signify that the same motors are suitable for the Long Island Railroad conditions where the distance between stops for most of the local runs is greater than that of the express runs of the subway, and the express runs are longer in proportion. More or less of the usual calculating must, therefore, be done to reach a decision as to whether the characteristics of the standard motor of this size are suitable for this service or whether a smaller size could be used to advantage.

In Volume 19 of the TRANSACTIONS of the A. I. E. E. and in the technical press of the last two or three years, there are a number of interesting papers giving theoretical and practical information regarding electric motors for railway service. Of these papers that of Messrs. Arnold and Potter on Acceleration Tests gives some very interesting results of actual records of speed-time tests of steam and electric trains of different weights, illustrated by diagrams which admit of close comparison between theoretical and practical results. The scholarly and somewhat bewildering papers by Mr. Mailloux and by Dr. Hutchinson are of interest as representing the academic side of some of the problems involved; and Mr. Gotshall contributes some very interesting illustrations of theoretical speed-time curves derived for a specific case. The subjects of train resis-

tance, acceleration rates, and rating of motors have been reported on at length and each investigator has viewed them from a different standpoint. The effect of the inertia of rotating parts of a train, previously neglected, has also been given its full share of importance. With all this information at hand, however, there are still some very pertinent questions which arise in the mind of an engineer approaching the solution of such a problem:

Who is right?

How much of this tedious calculating is necessary?

Whether used to overcome mechanical friction, head resistance, gravity, or inertia, how much power must be delivered to the motor cars to move a train from one terminus to the other?

How close will practice work out to theory?

What allowance must be made for local limitations on the possible speed of train equipments?

Some of the things that were done to obtain satisfactory answers to these questions may be of interest to the members of the INSTITUTE.

I. PLOTTED AND TEST RUNS COMPARED:

The power required to overcome inertia and gravity may be calculated with exactness. Train resistance, however, made up of head resistance, mechanical friction, and skin friction, may be estimated only by empirical formulas, based on practical tests. Such formulas have been derived and published by various engineers. Owing to differences in character of equipment and road-bed, nature of the train service, design of car bodies and trucks, methods of test, etc., there are material differences in the conclusions reached. For ordinary electric car service on urban and suburban lines, where the number of stops is frequent and the maximum speed is low, the train resistance is relatively unimportant as compared with the effect of inertia and grades, but as the speed increases the train resistance becomes a more important matter. The lack of agreement of these formulas when applied to the conditions of the L. I. R. R. are illustrated in Fig. 1. The Davis and the Baldwin Locomotive Works' formulas are extremes and they therefore afford a sufficient illustration of the divergence of authorities on this subject. These formulas are expressed as follows:

$$\text{Baldwin Locomotive Works, } R = 3 + \frac{V}{6.}$$

$$\text{W. J. Davis, } R = 4 + 0.13\,V + \frac{.004\,A\,V^2}{T}\,[1 + 0.1\,(n-1)]$$

R = Train resistance in lb. per ton of 2000 lb.
V = Velocity in miles per hour.
A = Cross sectional area of car in sq. ft.
T = Weight of train in tons of 2000 lb.
n = Number of cars per train.

The formula marked "Smith" is one suggested by one of the authors and has been found to give results close to actual practice as will be explained in the following paragraphs. This formula has the following expression:

$$R = 3 + 0.167\,V + 0.0025\,\frac{A}{T}\,V^2.$$

COMPARATIVE TRAIN PERFORMANCES COMPUTED WITH DIFFERENT RESISTANCE FORMULAS.

2-car train; weight, 70.6 tons; 2 Westinghouse No. 86 motors; 19:63 gear; 36-in. wheel; run, 1.67 miles, level; 540 volts.

Formula.	Time Seconds.		Per cent. Time	Speed miles	kw-hr	Watt-hr. per ton
	Total	Power on	Power on	per hr		Mile.
Davis	210	187	89	28.6	7.51	63.6
Smith	210	136	65	28.6	5.76	48.8
Baldwin Locomotive Works	210	103	49	28.6	4.66	39.5

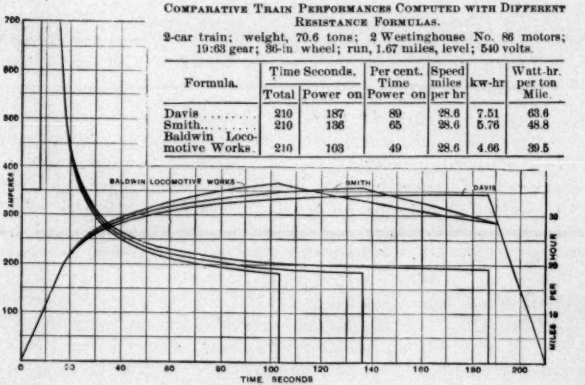


FIG. 1.

The speed-time curves in Fig. 1 are derived for a two-car train with cars of weight and dimensions similar to those of the Rapid Transit Railway in Manhattan. The length of run is an average for the total Long Island suburban service. It will be noted that the power consumption (watt-hours per ton mile) varies from 39.5 to 63.6, the figure according to Davis' formula being 61 per cent. greater than the Baldwin figure. Moreover if the conditions were such that the average speed of 28.6 miles an hour between stations had to be maintained, the speed-time curve of Davis would be impracticable because of no allowance

TABLE 1.

AVERAGE SPEED AND WATT-HOURS PER TON MILE

COMPARISON OF THEORETICAL RESULTS WITH ACTUAL TESTS.

G. R. G. H. & M. RY.

(Schedule speed the same.)

Two Westinghouse No. 50-C Motors. Weight of train 29.5 tons.

Test No.	Davis		Smith		Test	
	Miles per hour	Watt-hours per ton mile	Miles per hour	Watt-hours per ton mile	Miles per hour	Watt-hours per ton mile
1	27.9	98.	27.9	79.2	27.9	88.2
2	32.7	99.2	32.7	81.6	32.7	81
3	30.4	85.7	30.4	75.0	30.4	86.2
4	30.4	115.1	30.6	111.5	30.6	110.

D. Y. A. A. & J. RY.

(Schedule speed the same.)

Four Westinghouse No. 76 Motors. Weight of train 32 tons.

Test No.	Davis		Smith		Test	
	Miles per hour	Watt-hours per ton mile	Miles per hour	Watt-hours per ton mile	Miles per hour	Watt-hours per ton mile
5	28.3	99.	28.3	94.	28.3	99.
6	31.5	102.	31.5	96.	31.5	105.
7	33.4	95.	33.4	89.	33.4	97.

ARNOLD & POTTER TESTS.

(Power to be cut off at same distance from start, if possible. Schedule speed not the same.)

8 G. E. No. 55 Motors.

Test No.	Weight Train Tons	Davis		Smith		Test	
		Miles per hour	Watt-hours per ton mile	Miles per hour	Watt-hours per ton mile	Miles per hour	Watt-hours per ton mile
8	228.5	26.6	87.	27.6	72.	27.1	79.4
9	201.5	27.7	98.5	28.4	84.5	28.4	82.
10	175.5	29.2	102.	30.9	84.	29.9	86.9
11	148.5	29.6	111.	30.6	89.5	30.6	93.4

in coasting to provide for possible delays, etc. Therefore, whereas the Baldwin formula indicates a satisfactory equipment working with very low power consumption, the Davis formula for the same equipment shows relatively a very high power consumption and an impracticable equipment. The necessity of careful investigation of this matter in connection with our problem is apparent.

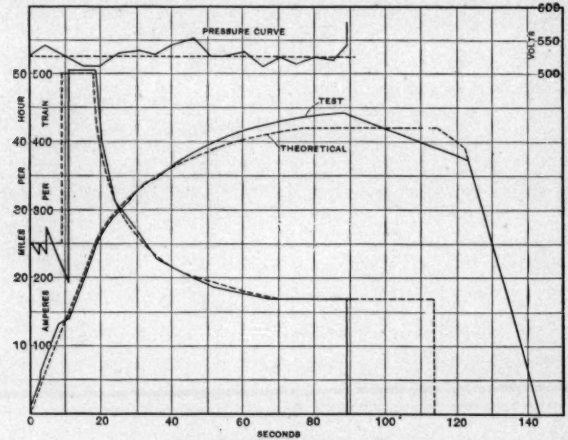


FIG. 2.

Test No. 2—G. R. G. H & M. Ry.

	Results. *Plotted.*	*Test.*
Time, seconds	144	144
Distance, miles	1.31	1.31
Schedule speed miles per hr	32.7	32.7
Kilowatt-hours	3.83	3.13
Watt-hr. per ton mile	99.2	81

Single car; weight 29.5 tons; 2 Westinghouse No. 50 C. Motors.

Davis formula used in plotting run.

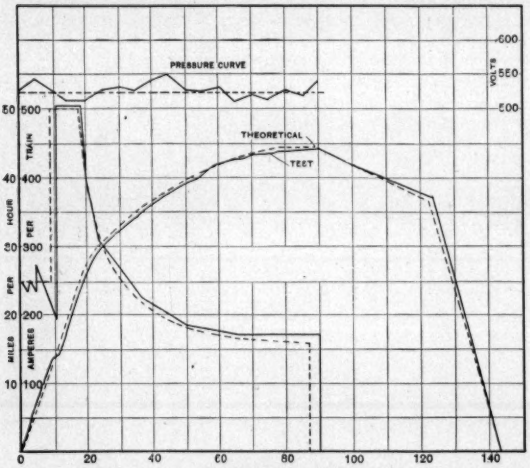
Note — Theoretical speed curves are corrected for variations in grade and pressure.

APPLICATION OF FORMULAS:

The essential points which we wish to determine are the schedule speeds which can be obtained with given equipments, the power that will be required to obtain these speeds, and the heating effect on the motors. The value of train resistance is best determined at full speed, or while coasting; but except

in the case of long runs most of the power is consumed in accelerating. By comparing actual test runs with plotted runs from start to stop, we get some check on the train resistance formulas, but, what is of more immediate importance, we get a verification of the accuracy of all the elements entering into our calculations.

To effect a comparison of theoretical results with actual tests,



FIG, 3.

Test No. 2—G. R. G. H. & M. Ry.

	Results.	
	Plotted.	*Test.*
Time, seconds.....	144	144
Distance, miles.....	1.31	1.31
Schedule speed miles per hr.	32.7	32.7
Kilowatt-hours.....	3.16	3.13
Watt hr. per ton mile.....	81.6	81

Single car; weight 29.5 tons; 2 Westinghouse No. 50 C. motors. *Smith* formula used in plotting run. Note — Theoretical speed curves are corrected for variations in grade and pressure.

some special tests were made on the Grand Rapids, Grand Haven and Muskegon Railway, and on the Detroit, Ypsilanti, Ann Arbor & Jackson Railway in Michigan. These tests were necessarily confined to trains of one car each. The tests reported by Messrs. Arnold and Potter, made at Schenectady, were on trains of greater lengths. To supplement the single-car

data, theoretical runs of trains of identical composition and equipment were plotted for comparison with some of these Schenectady tests. The various comparisons made are summarized in Table 1, which, therefore, shows the comparison of theoretical and actual results for trains of from one to eight cars per train.

On the G. R. G. H. & M. road the equipment consists of two

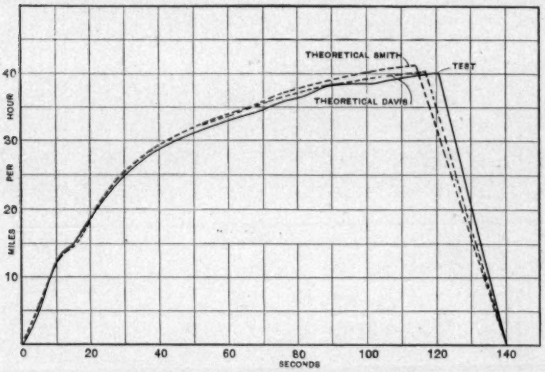


FIG. 4.

Test No. 5—D. Y. A. A. & J. Ry.

	Results.		
	Davis.	*Test.*	*Smith.*
Time, seconds.....	140	140	140
Distance, miles....	1.1	1.1	1.1
Schedule speed miles per hr.....	28.3	28.3	28.3
Kilowatt-hours....	3.49	3.49	3.33
Watt-hr. per ton mile.....	99	99	94

Single car; weight 32 tons; 4 Westinghouse No. 76 motors. *Davis* and *Smith* formulas used in plotting runs.

Note—Power cut off at same distance from start. Average speed between stops maintained constant by varying braking rate.

Theoretical speed curves are corrected for variations in grade and pressure.

150-h.p. motors mounted on a heavy Baldwin truck with Gibbs suspension. The unequipped truck is also of the Baldwin make and the entire equipment is of the highest standard. On the D. Y. A. A. & J. road the equipment consists of four 75-h.p. motors mounted on rather light trucks. Both roads have first-class roadbeds, well ballasted, and laid with 70-lb. rails of standard A. S. C. E. section. The tests were made on sections of track

practically straight and level. A chronograph was used to determine the speed at every revolution of the wheels, and the current and pressure were read by observers simultaneously at five-second intervals. From these tests speed-time and current-time curves were plotted. In making these tests the instructions were to accelerate and brake at as high a rate as practicable; therefore, the curves obtained may be considered as representing the limit obtainable in practice with the existing conditions.

For comparison with these actual results, theoretical runs were plotted in which the length of run was made the same, the average speed was made the same where possible, and the average rate of braking was assumed to be the same as in the actual experiments. The curves were corrected for pressure and grade so as to conform as closely as possible to the conditions prevailing during the test. The observed current readings were plotted and also the assumed theoretical values of the current corresponding to calculated speeds. The watt-hours per ton-mile were calculated from the observed tests either from wattmeter readings or by multiplying together the simultaneous voltmeter and ammeter readings. In the case of calculated runs, the value was obtained by integration, proper allowance being made for variation in pressure. The results of all the various tests are shown in Table 1.

The characteristics of the test curves and the comparison with plotted runs on the G. R. G. H. & M. Ry. are illustrated by Figs. 2 and 3. The differences resulting from the use of the Davis or the Smith formula are also indicated.

The D. Y. A. A. & J. Ry. tests are also summarized in Table 1. The character of the results obtained is illustrated in Fig. 4. In these tests there was no coasting and the conditions were such as to cause a considerable drop in pressure during the first part of acceleration. This may have caused sufficient error in the readings to account for the lack of agreement between tests and the calculations based on the Smith formula. The power curves were plotted and the watt-hours per ton-mile were computed therefrom as in the other cases, but the current curves have not been reproduced in this Fig. on account of the difficulty of plotting them all without confusion.

The comparison between actual results and theoretical runs in the case of the Arnold and Potter tests was effected in the same manner as for the single car tests. See Table 1 and

Figs. 5, 6, 7, and 8. It is at once evident from the comparative curves and the table of results that either of the two formulas for train resistance is reasonably close to the actual conditions. The exhibits when analyzed lead to the following conclusions as to the relative applicability of the two formulas:

The acceleration curve from the Davis formula conforms more

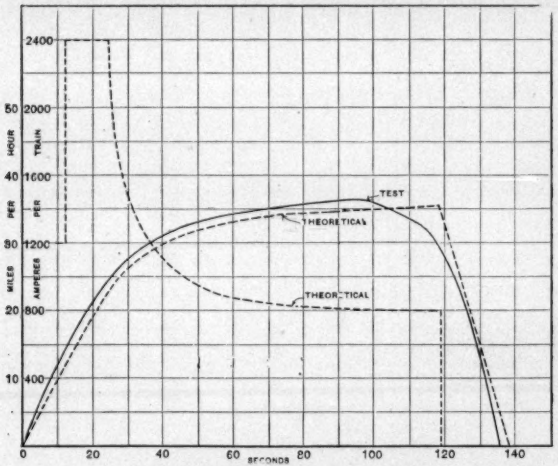


FIG. 5.

Test No. 8—Arnold & Potter. Run No. 1.

	Results. *Plotted.*	*Test.*	
Time, seconds.....	138	135.5	8 cars; weight 228.5 tons; 8 G.E. No. 55.
Distance, miles....	1.02	1.02	*Davis* formula used in plotting run.
Schedule speed miles per hr.....	26.6	27.1	Head wind, 15 miles per hr.
Kilowatt-hours....	20.3	18.5	Average pressure, 570 volts.
Watt-hr. per ton mile.....	87	79.4	Starting current, 300 amperes per motor. by wattmeter.

closely to the tests for the D. Y. A. A. & J. car, but for the G. R. G. H. & M. car and for the Arnold and Potter trains it falls below the actual curve, in some cases to such an extent that the theoretical schedule speed is below the actual even with coasting eliminated. The Smith formula gives accelerations practically coincident with the G. R. G. H. & M. tests

and somewhat higher than the actual for the other tests, the difference in any case not being sufficient to be misleading in the results as to schedule speed. This difference may easily be accounted for by difference in pressure or inaccuracies in observation of instruments. In the case of the D. Y. A. A. & J. car, the type of trucks or the drops in pressure may either of

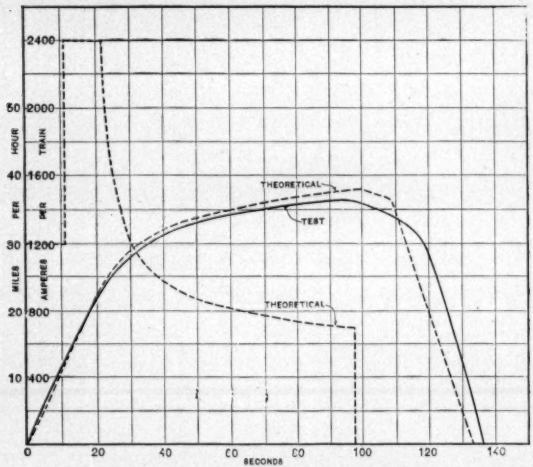


FIG. 6.

Test No. 8—Arnold & Potter. Run No. 1.

	Results. *Plotted.*	*Test.*
Time, seconds	133	135.5
Distance, miles	1.02	1.02
Schedule speed miles per hr.	27.6	27.1
Kilowatt-hours	16.7	18.5
Watt-hr. per ton mile	72	79.4

8 cars; weight 228.5 tons; 8 G.E. No. 55.
Smith formula used in plotting run.
Head wind, 15 miles per hr.
Average pressure, 570 volts.
Starting current, 300 amperes per motor.
by wattmeter.

them have caused the reduced acceleration. In the case of the Arnold and Potter tests the most decisive point in the comparison is the fact that whereas the use of the Smith formula permitted of cutting off the power at the same distance from the start as in the test, the Davis formula resulted in the theoretical runs in which the schedule speeds were lower than the

tests even when the power was applied up to the point where braking began. In other words, if the Davis formula be correct the trains could not have made the runs in the time that they actually did make without an excessive braking rate. The conclusion, therefore, is that the Smith formula most nearly represents the actual train resistance for all of these tests.

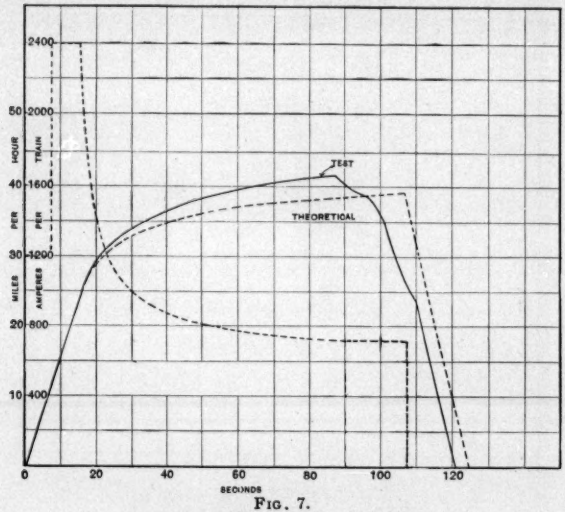


FIG. 7.

Test No. 11—Arnold & Potter. Run No. 7.

Results.	*Plotted.*	*Test.*
Time, seconds	124	120
Distance, miles	1.02	1.02
Schedule speed miles per hr.	29.6	30.6
Kilowatt-hours	16.7	14.3
Watt-hr. per ton mile	111	93.4 by wattmeter.

5 cars; weight 148.5 tons; 8 G.E. No. 55 motors.
Davis formula used in plotting run.
Head wind, 15 miles per hr.
Average pressure, 570 volts.
Starting current, 300 amperes per motor.

With reference to power required, the actual results appear to fall between the results obtained with either of the two formulas. The calculations based on the Smith formula are closer to the actual results in most cases. For the G. R. G. H. & M. car, where the acceleration curves agree, the watt-hours per

ton mile are also very close, and in the Arnold and Potter tests even with a reduced schedule speed the watt-hours per ton-mile are considerably greater for the Davis formula than for the observed tests. The conclusion reached is that the Smith formula affords a better basis for calculating the average speeds,

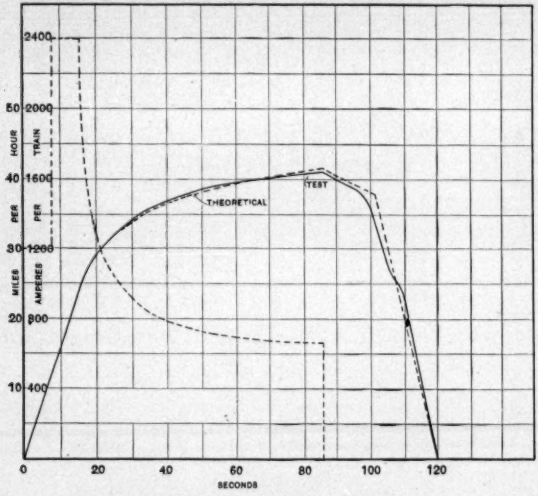


FIG. 8.

Test No. 11—Arnold & Potter. Run No. 7.

	Results. *Plotted.*	*Test.*
Time, seconds.....	120	120
Distance, miles....	1.02	1.02
Schedule speed miles per hr.....	30.6	30.6
Kilowatt-hours....	13.5	14.3
Watt-hr. per ton mile.....	89.5	93.4

5 cars; weight 148.5 tons; 8 G.E. No. 55.
Smith formula used in plotting run.
Head wind, 15 miles per hr.
Average pressure, 570 volts.
Starting current, 300 amperes per motor.
by wattmeter.

and is sufficiently close for the determination of power required. Furthermore the comparative results with these various train weights and types of motor, give us a confidence in all the assumptions made and in the customary use of the motor curves and other data furnished by the manufacturers.

Test of Equipment Similar to that Proposed for the Long Island Railroad.

Through the courtesy of the Interborough Rapid Transit Company and Westinghouse Electric & Manufacturing Company it is possible to present the record of a special test which

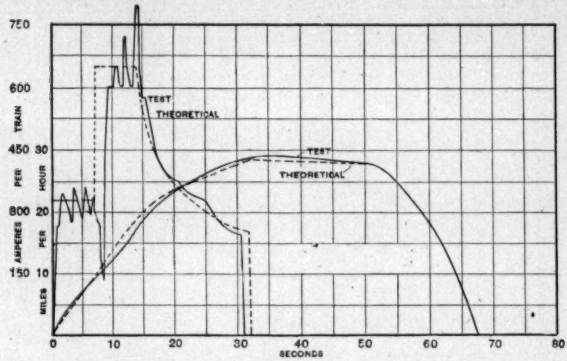


Fig. 9.

Comparison of Test and Theoretical Train Curve Using Actual Braking Curve.

Test made on 9th avenue line of Manhattan Ry. Co., Jan. 30, 1903.

Pressure 580 volts; 1 motor car; 1 trailer; weight 62.5 tons; distance 2065 ft., 93d Street to 104th Street; 2 Westinghouse No. 86 motors; gear 19:63; 33-in. wheels.

	Results.	
	Test.	*Theoretical.*
Average speed without stop	20.9	20.9
Schedule speed with 15 sec. stop	17.05	17.05
Kilowatt-hours per run	1.93	2.13
Kilowatt-hours per car mile	2.475	2.72
Watt-hours per ton mile	79.3	87.2
Average kilowatts per train	84.3	92.9
Sq. root mean sq. current per motor for 85 sec.	149.0	157.5
Starting current per motor	294.	325.

Smith formula used in plotting run.

has a direct bearing on this subject, because the type of motor equipment used in the test is the same electrically as that recommended for the L. I. R.R. project. On January 30, 1903, a test was made on the Ninth Avenue line of the Manhattan Elevated Railway, of the sample motors submitted by the Westinghouse Electric & Manufacturing Company as represent-

ing the motors which that company was to furnish to the Interborough Rapid Transit Company. In these tests the train weight corresponded closely with the weight per motor of the equipment proposed for the L. I. R.R. and the motors were of the same size and general characteristics. The length of the test run was too short to permit the cars to reach maximum

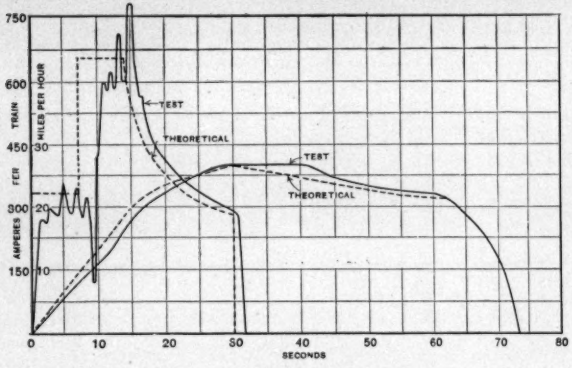


FIG. 10.

COMPARISON OF TEST AND THEORETICAL TRAIN CURVE USING ACTUAL BRAKING CURVE.

Test made on 9th avenue line of Manhattan Ry. Co., Jan. 30, 1903.

Pressure 580 volts; 1 motor car; 1 trailer; weight 62.5 tons; distance 2090 ft., 104th Street to 93d Street; 2 Westinghouse No. 86 motors; gear 19:63; 33-in. wheel.

	Results.	
	Test.	*Theoretical.*
Average speed without stop	19.32	19.32
Schedule speed with 15 sec. stop	16.10	16.10
Kilowatt-hours per run	1.91	2.06
Kilowatt-hours per car mile	2.415	2.65
Watt-hours per ton mile	77.0	83.0
Average kilowatts per train	77.3	82.5
Sq. root mean sq. current per motor for 85 sec.	145.2	157.0
Starting current per motor	300.0	325.0

Smith formula used in plotting run.

speed; as the value of train resistance is best determined at maximum speed, this test cannot by itself be considered an absolute check on calculated curves.

When viewed in the light of tests of other equipment on longer runs, however, it affords a good indication as to how close this specific equipment will conform to the theoretical

basis of our determinations. The results of this test are given in Figs. 9 and 10. Fig. 9 gives the results of a north-bound run between 93d Street and 104th Street, and Fig. 10 gives results for a south-bound run on the same section of road. Actual results are indicated by the solid lines, and for comparison there are given on the same Figs., theoretical curves calculated for the corresponding conditions, the train resistance formula and the methods used in the calculations being the same as for the other exhibits hereof and for all L. I. R.R. determinations. In these tests the braking rate was not constant but increased as the speed decreased, and for comparison the same braking curve was assumed for the theoretical as for the test runs.

The results in these comparative curves are tabulated under the respective Figs. The theoretical run was plotted to obtain the same average speed as the test. This involved assuming the power applied for a longer period than the test in one case and a shorter period in the other. In both cases, however, it will be noted that the power requirements (watt-hours per ton-mile) and the square root of mean square current are greater for the theoretical run than for the test. Furthermore, it will be noted that the average starting current per motor was less in the test than in the theoretical run. The conclusions derived from this exhibit are as follows:

(a) The motor control did not permit of the rapid application of power assumed in the calculations, time being lost in going from series to parallel. This, however, did not affect the results adversely.

(b) At the maximum speed when current was on, namely, 26 to 28 miles per hour, the theoretical curve shows practically the same energy consumption as the test. This indicates that the train resistance was practically as calculated. For corresponding speed on the motor curve, the power required according to theory is in both cases slightly higher than the power required according to test; this indicates that the Smith formula gives a train resistance which is slightly higher than the actual resistance for this equipment. The Davis formula, giving higher values than Smith would give results still further from the actual conditions.

(c) The calculations for energy consumption and square root of mean square current give results slightly higher than the test.

(d) The theoretical methods, therefore, give values which are slightly on the safe side for short runs.

(e) The tests do not afford direct evidence of the accuracy of the theoretical methods when applied to longer runs with higher speeds, but the indications are that for such runs the theoretical values will also be on the safe side and close enough for all practical purposes.

II. Use of Typical Run Curves:

As previously stated, the proposed electrical schedule for the Long Island Railroad provides for a large number of combinations of weights of trains and lengths of run. It is obvious that a very great amount of time would be consumed

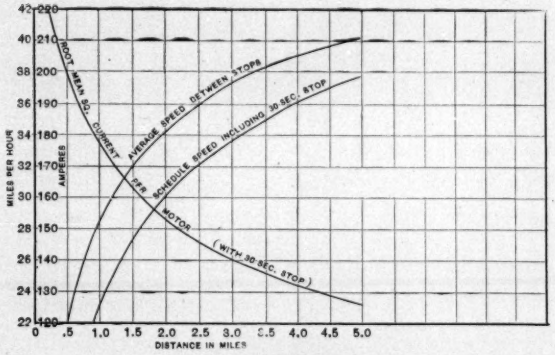

MILES PER HOUR
AMPERES
ROOT MEAN SQ. CURRENT PER MOTOR
AVERAGE SPEED BETWEEN STOPS
SCHEDULE SPEED INCLUDING 30 SEC. STOP
(WITH 30 SEC. STOP)
DISTANCE IN MILES
0 .5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0
42 40 38 36 34 32 30 28 26 24 22
220 210 200 190 180 170 160 150 140 130 120

Fig. 11.

General Performance Curve.

3-car train for L. I. R.R.; two 44-ton motor cars; one 33-ton trailer car; total weight 121 tons; four No. 86 Westinghouse motors; 23:59 gear ratio; 36-in. wheel; 540 volts; 1.5 miles per hr. per sec. braking; no coasting.

if an attempt were made to plot each of these runs and to make the determinations of schedule speed, power consumption, and heating effect for the various types and sizes of motors which might be used. To avoid this expenditure of time it was necessary to adopt certain approximate methods, and one method which was used after verification by a practical comparison, is what may be called the "Typical Run Curve."

Disregarding grades and curves, a single run for a distance equal to the average length between stops will represent the

TABLE 2.

ROCKAWAY PARK DIVISION.

77-ton Train. Two Westinghouse No. 86 Motors. 30-second stop. No Coasting

Run.	Length of Run	Square root of mean square current.			
		Plotted Run East	Plotted Run West	Average Plotted Both Ways	Typical Run.
Long Island City					
Bushwick Junction	3.92	154.5	137.3	145.9	147.9
Fresh Pond Junction	.46	223.9	227.0	225.4	226.8
Glendale Junction	1.61	178.2	179.0	178.6	179.3
Brooklyn Hills	.65	241.7	220.5	231.1	215.0
Woodhaven Junction	.97	186.5	207.0	196.7	200.2
Ozone Park	.30	227.0	274.0	250.5	240.0
Aqueduct	1.34	176.0	192.0	184.0	186.8
Ramblersville	.73	201.5	210.5	206.0	210.0
Howards	.76	209.5	207.0	208.2	209.3
Goose Creek	.93	201.7	200.5	201.1	201.8
The Raunt	.96	200.5	209.8	205.1	200.6
Broad Channel	.83	205.7	203.5	203.1	205.7
Beach Channel	.74	210.5	208.5	209.5	209.9
Hammel	.47	225.0	231.0	228.0	226.0
Holland	.39	229.5	210.5	220.0	232.0
Seaside	.49	227.5	224.5	226.0	229.4
Rockaway Park	.75	209.5	209.6	209.5	209.6
Average for round trip	.948	199.0	201.9	200.45	201.2

TABLE 3.

NORTH SIDE DIVISION

77-Ton Train. Two Westinghouse No. 86 Motors. 30-second stops. No Coasting.

Run.	Length of Run	Square root of mean square current.			
		Plotted Run East	Plotted Run West	Average Plotted Both Ways	Typical Run.
Long Island City					
Woodside	3.04	165.5	150.1	157.8	156.
Winfield	1.00	194.0	202.7	198.3	199.
Elmhurst	.81	210.5	202.0	206.2	207.
Corona	.92	215.0	210.0	212.5	202.
Whitestone Junction	1.20	179.8	195.8	187.8	191.5
Flushing, Main Street	1.98	209.9	195.0	202.4	171.5
Murray Hill	.90	237.0	195.5	216.2	203.
Broadway	.54	223.9	218.0	220.5	221.
Auburndale	.78	224.0	226.0	225.0	208.
Bayside	.97	208.5	202.0	205.2	200.
Douglaston	1.26	174.0	186.0	180.0	180.3
Little Neck	.55	233.0	225.0	229.0	220.5
Great Neck	1.24	199.3	165.5	182.4	190.
Manhasset	1.53	202.8	202.0	202.4	181.3
Port Washington	2.66	168.0	158.0	163.0	160.5
Average sq. root mean sq. for whole run	1.20	198.0	191.5	195.0	191 0
Average for round trip		24.2	24.9	24.55	24.

conditions pertaining to a through run; by plotting results for such average runs of different lengths, curves are obtained which will give exact results for the actual conditions assumed, and approximate results for the varying distances between stops and on a succession of light grades and curves. Fig. 11 illustrates the character of the curves obtained in this way.

The principal question involved as to the propriety of such a typical run curve is whether the result so obtained (by considering the track straight and level and the distance between all stops the same) will agree closely enough with the average of results obtained from plotting the time-speed curves of an entire round trip, taking the grades and curves into account and placing the stops exactly. It would seem reasonable that the effects of grades in one direction should balance those in the opposite direction when calculating the general results of a run plotted for a round trip, when the time of a single run is not greater than one hour, as in this case. If the results of train runs plotted complete be compared with typical run curve results, and if this comparison is generally favorable under varying conditions of grade and length of run, it is safe to assume that typical run curves can be used in place of plotted runs for purposes of general estimate and comparison of different types of equipment when operated under similar conditions. The comparisons have, therefore, been made for a given equipment by making plotted runs in opposite directions over the same grades on certain routes of the Long Island R.R. both on the comparatively level runs of the Manhattan Beach and Rockaway Beach divisions and on the more hilly runs from Long Island City to Port Washington. Tables of two of these runs are appended hereto (Tables 2 and 3), which give values for the square root of mean square current for individual runs between stops and the average for round trips. It is to be noted in passing that these particular tables represent motor performances that proved too heavy for the motors and had to be abandoned. They, however, illustrate the point under discussion.

It is possible to make similar comparisons for kilowatt-hours per car-mile and watt-hours per ton-mile, but it is safe to assume that a check made on the comparative determinations for square root of mean square current will indicate the correctness of the assumptions for the determination of the other requirements.

In general it will be noted that the differences between typical run results and the plotted runs, even in the case of the North

Side Division, on which conditions of grade are most severe, do not exceed five per cent. for the square root of mean square current and about four per cent. for speed. This would seem to be sufficiently close for practical purposes in making estimates for given equipment operated over runs of varying lengths where grades are so comparatively light as in the case of the Long Island R.R.

A verification of the accuracy of this method for power determinations in service on an interurban road of the normal

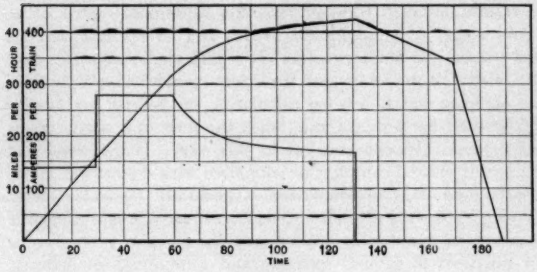


FIG. 12.

AVERAGE PERFORMANCE IN SERVICE, OF G. R. G. H. & M. RY. CAR.

Two Westinghouse 50 C. motors; 20:51 gear ratio; 0.55 miles per hr. per sec. initial acc.; 525 volts; 140 amperes per motor starting current; weight 29.5 tons; average grade, level.

	Results.	
	Theoretical.	*Observed average.*
	G. R. G. H. & M. Ry.	
Distance, miles	1.54	1.54
Time, seconds	188	188
Schedule speed miles per hr.	29.5	29.5
kilowatt-hours	3.84	3.65
Watt-hr. per ton mile	84.5	80.3
Root mean sq. current, amperes	95.6	

Smith Formula.

amount of curvature in a comparatively level country is obtained by plotting an average run for the G. R. G. H. & M. road, Fig. 12 shows a run plotted for the same distance, time, initial acceleration, and percentage of time coasting and braking as averaged on a round trip service run of a single car of the G. R. G. H. & M. Ry. outside of terminal cities. The tabulated data under this Fig. shows that the watt-hours per ton-mile were within six per cent. of the same value for the theoretical average as for the observed average of an actual test.

The foregoing examples demonstrate that for preliminary determinations of motor characteristics, reasonably close results are obtained by assuming a typical run, except possibly where very unusual conditions exist. No claim is made that the method is new; in fact it is quite generally used. The data given simply show that under ordinary circumstances it is reasonable to use this short method and thus dispense with a large amount of tedious calculating.

III. Schedule Speed Requirements and Limitations:

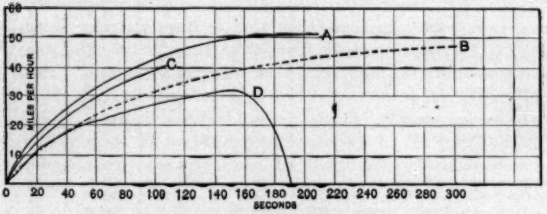


Fig. 13.

Time-Speed Curve of 3-Car Steam Train.

A.—From best locomotive performance reduced to level. Weight of train, including locomotive No. 59, 171.9 tons disregarding light live load. Weight of locomotive, including tender, 88.5 tons. Weight on drivers, 37.5 tons.

Time-Speed Curve of 5-Car Steam Train.

B.—From best locomotive performance reduced to level. Weight of train, including locomotive No. 64, 232.6 tons disregarding light live load.

Time-Speed Curve of 3-Car Steam Train.

C.—From actual run made on a level. Weight of train, including locomotive No. 72, 175.1 tons, disregarding light live load.

Time-Speed Curve of 5-Car Steam Train.

D.—From actual run made on a level. Weight of train, including locomotive, No. 64, 232.6 tons disregarding light live load.

The operating conditions of a large steam railroad introduce limitations which cut down the possible speed of the motive power equipment. Many of these are conditions which do not relate to the nature of the equipment and over which the locomotive engineer has no control; for instance, curves, road crossings, junction points, yard limitations, meeting points on single track lines, time to handle baggage and express matter, etc. There are delays at stations and delays during runs, some of which occur regularly, but many of which are intermittent. Because of the complicated service these delays are

TABLE 4.
LONG ISLAND RAILROAD.
LONG ISLAND CITY TO VALLEY STREAM VIA FAR ROCKAWAY. EASTBOUND.
Length of Run, 22.97 miles.

Train Number.	1287	1303	1321	Average
Locomotive number	72	34		
Locomotive weight	179,000	154,500		
Number of cars	3	4	5	4
Total weight of train (tons)	175.1	186.55		
Schedule time of run	56:00	55:00	58:00	56:00
Actual time of run	52:30	74:20	59:00	62:00
Schedule number of stops	9	10	12	10
Actual number of stops	10	11	12	11
Maximum acceleration	.6	.7	.65	.65
Grade on which made	-1.00	-0.08	-0.08	-0.38
Maximum retardation	1.6	1.8	1.9	1.76
Grade on which made	Level	Level	Level	Level
Average acceleration	.47	.46	.35	.426
Average retardation	1.04	1.06	1.22	1.11
Maximum speed	56.5	52.5	50.	53.
Average length of run	2.08	1.91	1.77	1.92
Average time of run	4:03	4:48	4:10	4:20
Average maximum speed	39.9	34.8	33.5	36.1
Length of longest run	7.77			
Time of longest run	11:20			
Average time of stops	0:49	1:55	0:25	0:63
Average speed between stops	30.8	23.9	25.5	26.
Possible average speed from curve	34.5	33.7	32.7	33.7
Ratio average to possible average speed	89.4%	71.%	76.%	79.6%

TABLE 5.
LONG ISLAND RAILROAD.
WHITESTONE DIVISION. WESTBOUND.
Length of run, 11.75 miles.

Train Number.	346	360	318	Average
Locomotive number	59	35	20	
Locomotive weight	177,000	154,500	139,500	
Number of cars	3	3	5	4
Weight of train (tons)	171.9	162.85	217.85	184.2
Schedule time of run	28:00	28:00	31:00	29:00
Actual time of run	28:34	27:34	35:15	30:27
Schedule number of stops	7	7	7	7
Actual number of stops	7	7	7	7
Maximum acceleration	.9	.95	.5	.78
Grade on which made	-0.65	-0.65	-0.75	-0.68
Maximum retardation	1.8	2.0	1.9	1.9
Grade on which made	1.07	0.69	1.28	1.01
Average acceleration	.44	.35	.29	.36
Average retardation	1.43	1.5	1.2	1.38
Maximum speed	52	50	44.5	48.8
Average length of run	1.47	1.47	1.47	1.47
Average time of run	3:08	3:14	3:55	3:26
Average maximum speed	41	38.3	33.5	37.6
Length longest run			1.62	
Time longest run			3:47	
Average time at stops	0:29	0:15	0:33	0:26
Average speed between stops	28.1	27.3	22.5	25.9
Possible average speed from curve	30.8	30.8	30.8	30.8
Ratio actual to possible average speed	91.3%	88.6%	73%	84.2%

greater on the suburban lines of a steam road than usually occur in interurban or elevated electric service. It is, therefore, evident that in the electrical operation of such suburban service the loading of the motors will differ materially from the loading in an ideal run which might be made with the conditions removed.

After considering various methods of providing for these conditions it was decided to make a series of tests of the present steam equipment to determine the speed time characteristics of the steam trains and the degree to which these characteristics are affected by the local conditions. To this end a test car was equipped with a speed-recording device and runs were made over various routes with this car attached to regular trains. Complete records were obtained of the movement of each train throughout a round trip, and observations made of local conditions which affect speed. These records were carefully analyzed and the results tabulated. In some instances the engineers were requested to make the best time possible; in other cases they were not advised that a test was in progress.

In summarizing these test runs comparisons were made between the average speed between stops as actually attained and the possible average speed if best acceleration had been made for each run. The character of record obtained is illustrated in Tables 4 and 5. It was found that the ratio of the actual speed to the possible speed without local limitations is from 71 to 91.3 per cent. Even when the engineers were requested to do their best they were able in only one or two instances to exceed 90 per cent. of the speed which appeared from the test to be possible. On runs 335 and 346 of the Whitestone Division in which locomotive No. 59 made the best single record, the average speed for the run was also nearest to the maximum limit.

From these records were selected the four best single accelerations. Fig. 13 shows the speed-time characteristics of these accelerations. Curve D illustrates the general character of record made by the instrument in these tests. This run, having been made on a level, conforms exactly with the record obtained. Curves A and B were obtained on grades, and the actual record has been corrected to illustrate the performance of these trains when reduced to a level. In each case the average acceleration over the run was less than the characteristic shows, but these curves illustrate the maximum that

the steam equipment was able to do. The composition of trains and their estimated weights are indicated under Fig. The live load on these runs was so light that it was disregarded. On Fig. 14 will be found two curves (E and F) of actual runs on grades, compared with run A of the Fig. 13. According to curve E, a five-car train on a down grade was accelerated at a rate far below the best performance and even the three-car train with locomotive No. 35 (curve F) was not accelerated on a down grade with a rate any better than the best single performance on a level.

It will be noted that the curve *A* was made by a locomotive

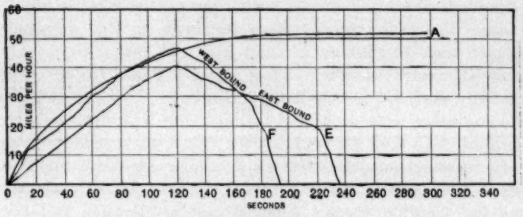


FIG. 14.

TIME-SPEED CURVE OF 3-CAR STEAM TRAIN.
A.—Taken from curve sheet No. 13.

TIME-SPEED CURVE OF 5-CAR STEAM TRAIN.
E.—From College Point to Whitestone, made by 5-car steam train. Weight, including locomotive No. 18, 276.1 tons disregarding small live load. Acceleration made on average grade of –0.78 per cent.

TIME-SPEED CURVE OF 3-CAR STEAM TRAIN.
F.—From Whitestone to College Point, made by 3-car steam train. Weight, including locomotive No. 35, 162.85 tons, disregarding small live load. Acceleration made on average grade of –0.74 per cent.

whose weight was 51.5 per cent. of the total weight of train. The officials of the railroad were of the opinion that service equivalent to that which could be performed by this locomotive, No. 59, with only three cars would be sufficient for the electric equipment. The best performance of this locomotive was, therefore, taken as the criterion by which to work in determining the proper characteristics for the electric equipment. The condition laid down was that the electrical equipment, operating a train with standing load in the cars, should be able to make the same average speed between stops as this particular steam equipment.

TABLE 6.

DATA FOR SUBURBAN RUNS. L. I. R.R.

OMITTING RUNS WHERE NUMBER OF STOPS IS SAME AS HEREIN BUT TIME AT STOPS IS LESS.

Run.	Distance miles.	Time minutes.	Train sheet schedule speed entire run.	Intermediate No. of stops per trip.	Time out for stops.	Average Length of Run miles.	Time of average Run minutes.	A. Average speed between stops miles pr hr	B. Limit av. speed best steam train miles pr hr	Ratio of $\frac{A}{B}$ steam.	C. Limit average speed electric train 23:59 gear ratio.	Ratio $\frac{A}{C}$ Electric.
Long Island City. Port Washington.	18.18	41.5 43.0	26.3 25.4	7 8	4.5 5.0	2.27 2.02	4.62 4.22	29.5 28.7	36.0 34.0	81.9 84.4	35.5 34.0	83.2 84.5
Long Island City. Whitestone Landing.	11.75	31.0	22.8	7	3.5	1.47	3.44	25.6	30.8	83.2	31.8	80.5
Long Island City. Rockaway Park.	16.3	39.25 39.0 40.0 41.0 43.0 43.75 47.0	24.9 25.1 24.4 23.8 22.8 22.3 20.8	5 6 7 8 10 11 14	2.5 2.75 3.5 4.25 4.0 4.5 5.5	2.72 2.33 2.04 1.81 1.48 1.36 1.09	6.12 5.18 4.57 4.08 3.55 3.27 2.76	26.7 27.0 26.8 26.6 25.0 25.0 23.7	37.5 36.0 34.0 33.0 30.8 30.0 27.0	71.2 75.0 78.8 78.8 81.2 83.3 88.0	36.5 35.5 34.0 33.5 31.8 31.0 29.0	73.2 76.1 78.8 79.5 78.7 80.7 81.8
Long Island City. Valley Stream.	22.97	59.5	23.1	11	7.5	1.91	4.33	26.4	33.7	78.4	33.7	78.3
Long Island City. Manhattan Beach.	16.1	37.0 38.0 40.0 44.0	26.1 25.4 24.2 22.0	3 4 5 11	3.0 2.5 3.75 6.5	4.03 3.22 2.68 1.34	8.5 7.1 5.87 3.12	28.5 27.2 27.4 25.8	41.0 39.0 37.5 29.8	69.5 69.8 73.2 86.5	39.0 37.5 36.5 31.3	73.0 72.6 75.0 82.5
Flatbush. Rockaway Park.	15.88	39.5 44.75 45.5 47.0 48.0	24.5 21.5 20.9 20.2 19.8	7 11 12 15 16	4.0 5.0 5.75 6.5 6.75	1.98 1.32 1.22 0.99 0.93	4.56 3.31 3.06 2.53 2.43	26.0 23.9 23.9 23.5 23.0	34.0 29.5 28.5 26.5 26.0	76.5 81.2 84.0 88.6 88.5	34.0 31.0 30.0 28.5 28.0	76.5 77.2 79.6 82.5 82.2
Flatbush. Jamaica.	9.63	19.0 23.0	30.4 25.1	1 5	1.0 3.0	4.81 1.61	9.0 3.33	32.0 29.0	42.5 31.5	75.3 92.1	40.0 32.5	80.0 89.2
Flatbush. Valley Stream.	22.55	60.5	22.4	13	9.0	1.61	3.68	26.1	31.8	82.0	32.0	82.4

Taking curve *A* as a basis, determinations were made of what may be termed the "speed-limit" for steam trains. This is a curve indicating the average speed in miles per hour between stops with the rate of acceleration corresponding to curve *A*, without coasting, and with a braking rate of 1.5 miles per hour per second. On Fig. 15 there will be found a characteristic speed-time curve of this steam train making runs of from one mile to three miles. From this curve the speed-limit curve No. 16 was plotted. Table No. 6 shows how this speed-limit of steam trains compares with the average speed between stops required to make various typical runs of the proposed suburban service. It will be noted that the average speed of the schedule runs is from 71.2 to 92 per cent.

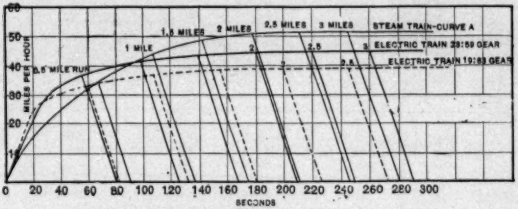


FIG. 15.

TIME-SPEED CURVE OF STEAM TRAIN.
Curve *A* of sheet No. 13.

TIME-SPEED CURVES OF PROPOSED ELECTRIC TRAINS.
Best possible performance on level grade.
Weight of train, 121 tons, with standing load.
(All 3-car trains.)

of the speed limit, with about 80 per cent. as a mean figure.

SCHEDULE CONDITIONS OF PROPOSED ELECTRIC SERVICE:

Obviously, to make the same time, the speed characteristics of the electric equipment selected for this service must be such that the schedule can be maintained with similar speed reserve, unless the limiting conditions are removed. Some of these conditions are being removed and others probably will be. Elimination of grade crossings at roads and junction points, handling of baggage and express matter by special trains, improvement of yard facilities, etc., will make it possible to operate trains at speeds closer to the limit of the equipment. On the other hand, as the population along the road increases the ten-

dency will be to increase the number of stops with as little increase as possible in the running time; therefore, it was decided not to make any material allowance for improved conditions in the initial service. The probability of such improvement, however, suggests another precaution to be taken in the selection of equipment; namely, the provision of a suitable reserve in capacity of motors to carry the greater loads which will result from running at speeds closer to the limit.

On Fig. 15 are time-speed curves of a three-car electric train with two motor cars and one trailer, with standing load in the cars, which curves may be compared with the corresponding curve of the steam train on the same Fig. It

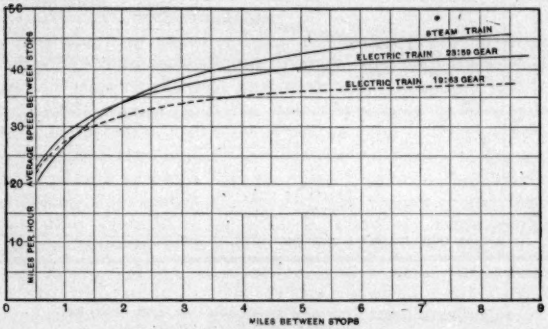


FIG. 16.

SPEED LIMIT CURVES FOR 3-CAR TRAINS.

Showing best possible speed between stops over various lengths of run, without coasting.

Steam train based on curve *A* for acceleration.

Electric train with standing load weighs 121 tons.

will be noted that the electric equipment with the lower gear ratio has a maximum speed on straight level track of approximately 45 miles per hour, and with the higher gear ratio, 39 miles per hour; whereas the limit of the steam train on the level is 52 miles per hour. For a run of one mile or less between stops, however, the electric train with either gear ratio makes better time than the steam train. For a 1.5-mile run the electric train with higher gear ratio falls behind the steam train, and at slightly over two miles the electric train with the lower gear ratio falls behind.

The comparative speeds of these trains are still better illustrated on the speed-limit curves of Fig. 16. The general average length of run between stops for the suburban service is about 1¾ miles. It is evident from the speed-limit curves on curve sheet 16 that a three-car electric train with two motor cars and gear ratio 23:59 will average slightly better as to speed than the three-car steam train, but that the same equipment with higher gear ratio falls considerably below the speed-limit of the steam train. From this exhibit it is ob-

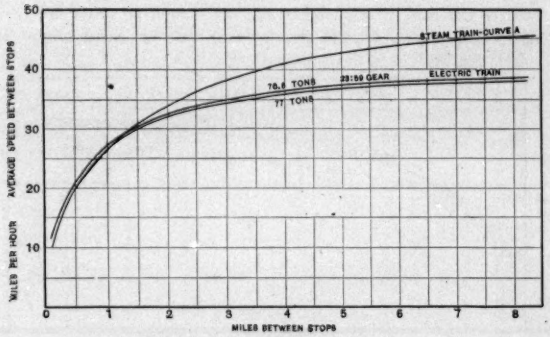


FIG. 17.

SPEED LIMIT CURVES FOR MOTOR CAR AND TRAILER.
Compared with steam train.
Electric train weighs 70.6 tons, seated load.
Electric train weighs 77 tons, standing load.
Steam train based on curve *A* for acceleration.

vious that schedule requirements dictate that no gear ratio higher than 23:59 should be adopted.

It is also evident from these speed-limit curves that if 23:59 is the lowest gear ratio practicable as determined by limitations, the three-car train unit will have to be made up of two motor cars and one trailer, in order that the requisite speeds may be reached. The weight per motor for this equipment is 30.3 tons, which on this basis of speed requirements is obviously close to the limit. This is also made evident by the speed-limit curves of Fig. 17. In this case a two-car train is made up of one motor car and one trailer. It will be

noted that such an electric train, with standing load, falls below the speed-limit of the steam train at slightly over one mile between stops. As regards speed requirements, therefore, the two-car train with motor car and trailer has not sufficient motor capacity, and except in cases where speed limitations are slight, two-car trains will have to be made up of two motor cars in order to make the schedule. On this Fig. 17, the corresponding curve for train with seated load has been plotted to indicate the difference in schedule speed possible during the light traffic hours of the day, as compared with the hour of heavy load morning and evening. It will be noted that in the case of heavy equipment of this character the changes in weight of live load do not materially affect the speed characteristics of the equipment.

Attention was called to the column of Table 6 which shows the ratio between the average speed of steam train between stops on different runs according to schedule, and the speed-limit possible with the best steam train in each case. Another column of this table gives the ratio of average speed to the speed-limit of the three-car electric train for the same runs. It will be noted that the reserve speed in the electrical equipment corresponds closely with the reserve in the steam equipment throughout the list. It, therefore, seems evident that this three-car train unit fulfils the requirements laid down as to speed, and can be depended upon to make the required schedule with standing load in the cars, allowing for all the delays contemplated in the present schedule for steam equipment.

It is obvious that trains made up into combinations of motor-cars and trailers that give less weight per motor will be able to make better speeds than indicated for this three-car train. Furthermore, as the number of cars per train increases, the relative effect of head resistance decreases. For these longer trains it is, therefore, possible that a greater proportion of trailer cars may be used in some instances without reducing the speed-limit to such an extent as to prevent the train from making schedule time.

Conclusion.

It is not the purpose of this paper to follow out all the technical processes by which final conclusions were deduced as to size and characteristics of motor equipments for the project referred to. Sufficient illustrations have been given to show:

First, that a study of the operating conditions of even a

complex project quickly narrows the selection of motors down to one or two sizes, and that these conditions also largely determine the speed characteristics of the equipment; *secondly*, methods of computation are now developed to a point of sufficient accuracy to be considered reliable for purposes of selecting equipment; *thirdly*, short methods may be used with discrimination, at least for preliminary determinations.

With reference to the use of short methods, a remark may be made in closing regarding the advantage to be gained by deriving a set of general formulas, applicable to all sizes of motors. On first consideration, such a problem as herein described makes such data seem almost indispensable. When we find that only one or two sizes of motor need be considered, however, the advantage of so general a method becomes less apparent. On the other hand, with a little ingenuity, graphical or mechanical methods may be devised for plotting characteristic curves, which make it possible to determine the values of speed, current, etc., throughout a complete run with surprising rapidity. At the present state of development, therefore, it appears that the most satisfactory results may be obtained by employing the characteristics of a specific equipment rather than by spending time in deriving a set of hypothetical characteristics in which many important variables are neglected.

Discussion on "Problems of Heavy Electric Traction".

L. B. Stillwell: Probably no subject among the many which members of the Institute are called upon to consider is of greater practical interest at the present moment than that which is discussed in some of its phases in the interesting paper presented by Messrs. Lyford and Smith. Many points of view are possible, and the interdependence of questions involved in the selection of electric equipment to replace steam equipment in heavy electric traction service is such as to call for the exercise of great care and well-balanced judgment in deciding the important questions which require decision.

It is especially important that at a time when engineers whose experience in the field of traction is chiefly or wholly in that particular department which deals with tramway service, are for the first time called upon to advise in the broader field of heavy traction, they should at every step verify their theory by practical demonstration in order to make sure that nothing essential to a correct solution of the new problems is overlooked. The speaker feels, therefore, that the paper which Messrs. Lyford and Smith have presented is one of considerable practical value. He will not undertake to discuss it in detail, but has selected from the many interesting points discussed or touched upon in the paper a few which seem especially to suggest comment.

He desires to state at the outstart that the data set forth in Figs. 9 and 10 of the paper do not represent in respect to performance of the rheostatic control during acceleration the actual performance of the equipment used in the Subway. It is to be noted by inspection of the curves in Figs. 9 and 10 that the increments of current which follow the cutting out of successive rheostatic steps are very far from equal in amount, while not less than one second is lost in passing from series to parallel connection. Ideal performance would imply a uniform rate of increase of the current input from starting to the instant when the last resistance is cut out. Obviously, the curves shown are far from realizing this condition, and apparently they were constructed from runs made before the rheostats were properly adjusted. It is possible also that the irregularity of input increments is exaggerated by the fact that the measurements in these particular tests were made by simultaneous readings of non-recording ammeters and voltmeters. In the majority of tests which have been carried out by the engineers of the Interborough Company they were able to use, thanks to the courtesy of the General Electric Company, a most satisfactory outfit of automatic recording instruments which recorded simultaneously and continuously the current and pressure input; they also automatically constructed the time-velocity and time-distance curves; but these curves are not so satisfactory owing to the fact that their ordinates were determined

by a Boyer speed recorder which, as has been pointed out frequently, is not an entirely satisfactory instrument, particularly at low speeds.

The theoretical acceleration up to the point where all rheostats were cut out of circuit, as shown in Figs. 9 and 10, is apparently about 1.33 miles per hour per second, while the actual acceleration fell to 1.2 miles per hour per second. The theoretical acceleration for which the equipment of the Subway now in operation was adjusted was 1.50 miles per hour per second in the case of cars carrying no load, 1.30 miles per hour per second with a load of 9800 pounds per car, and 1.22 miles per hour per second with a load of 15 000 pounds per car.

The engineers of the Interborough Company have constructed many time-velocity curves, both actual and theoretical. They have considered various formulas, notably those used by the Baldwin Locomotive Works, the formula proposed by Mr. W. J. Davis, Wellington's formula, and a formula suggested by Mr. John Lundie. They have also made use of a curve suggested by the speaker's assistant, Mr. H. N. Latey, which is based upon consideration of the several formulas referred to and also upon numerous results of tests made by the writer and some of his assistants at various times during the last seven years. In the opinion of the speaker, all of the formulas referred to give for speeds under about 25 miles an hour values of train resistances too low for electric trains having from one-half to all axles equipped with geared motors. The fact that the Baldwin formula gives for all speeds values much lower than those derived by using the Davis formula is probably accounted for by the fact that the former is based upon tests of trail-cars only. Every one who has attempted to derive train friction from actual tests knows the difficulty of repeating, even once, the conditions obtained in an initial test. There are so many varying factors which enter into the train resistance that even at any given speed it is difficult to make a series of tests and obtain results which will check with any satisfactory degree of approximation. In the case of service like that of the local trains in the Subway, where the larger part of the power is used in local runs averaging about 1700 feet in length south of 96th Street and a little over 2000 feet north of that point, and where consequently fully two-thirds of the total energy delivered to trains is dissipated in braking, a considerable difference between the assumed and the actual train friction does not involve a corresponding difference in the resulting calculations of the power required. In the case of longer runs, it is obviously more important to have accurate quantitative knowledge of train friction.

For preliminary calculations under conditions of speed, length of run, and proportion of motor-equipped axles such as exist in the case of the Subway, the speaker believes that the assumption of an average of 13 lb. per net ton was reasonable

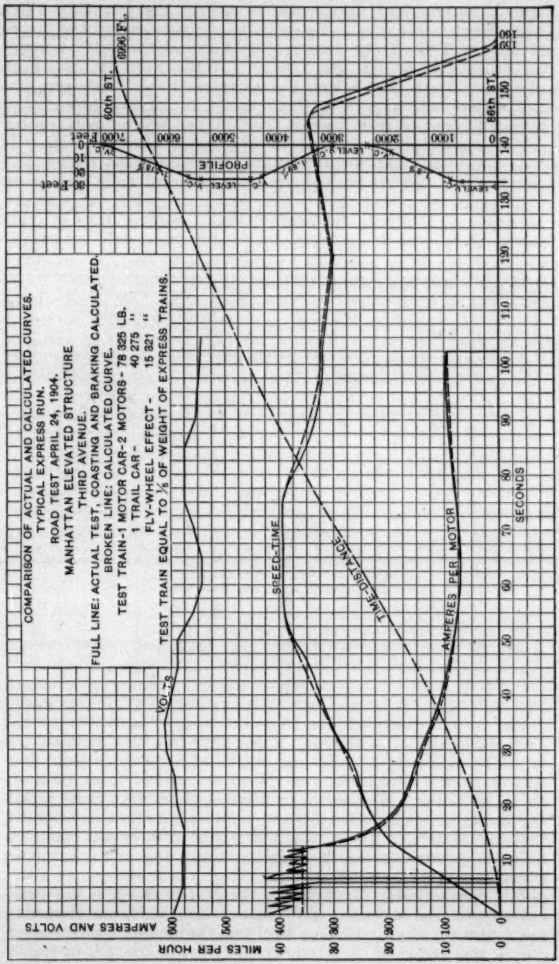

COMPARISON OF ACTUAL AND CALCULATED CURVES.
TYPICAL EXPRESS RUN.
ROAD TEST APRIL 24, 1904.
MANHATTAN ELEVATED STRUCTURE
THIRD AVENUE.
FULL LINE: ACTUAL TEST, COASTING AND BRAKING CALCULATED.
BROKEN LINE: CALCULATED CURVE.
TEST TRAIN-1 MOTOR CAR-2 MOTORS- 78 325 LB.
1 TRAIL CAR- 40 275 "
FLY-WHEEL EFFECT- 15 321 "
TEST TRAIN EQUAL TO ⅓ OF WEIGHT OF EXPRESS TRAINS.
PROFILE
60th ST.
6000 Ft.
59th ST.
LEVEL
SPEED-TIME
TIME-DISTANCE
AMPERES PER MOTOR
VOLTS
MILES PER HOUR
AMPERES AND VOLTS
SECONDS
Feet

FIG. 1.

and as satisfactory as the use of any of the formulas which have been considered. By way of supplementing the paper of Messrs. Lyford and Smith, Fig. 1 representing what might be called the typical express run of the Subway, has been plotted. Upon this figure, the theoretical run is shown, also the actual test run; the theoretical run having been based upon an assumed train friction of 13 lb. per net ton, with proper correction for grade and for variation in applied pressure. It is to be noted that the agreement shown between theory and test is close. From the fact that the assumed train friction in this instance appears to be sufficiently accurate for practical purposes, it is not to be inferred that the same train friction would show equally satisfactory results for speeds materially

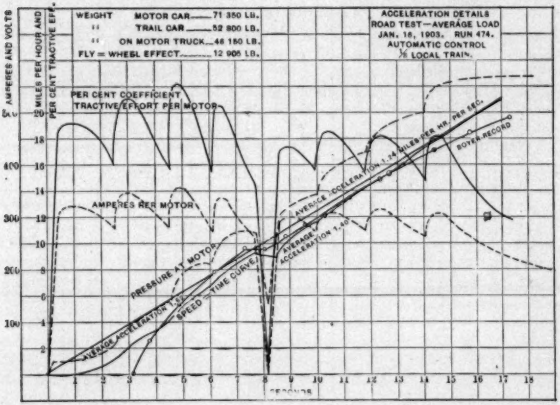

WEIGHT MOTOR CAR 71 350 LB.
" TRAIL CAR 52 800 LB.
" ON MOTOR TRUCK 46 150 LB.
FLY = WHEEL EFFECT 12 905 LB.
ACCELERATION DETAILS
ROAD TEST—AVERAGE LOAD
JAN. 16, 1903. RUN 474.
AUTOMATIC CONTROL
½ LOCAL TRAIN.
PER CENT COEFFICIENT TRACTIVE EFFORT PER MOTOR
AMPERES PER MOTOR
AVERAGE ACCELERATION 1.14 MILES PER HR. PER SEC.
AVERAGE ACCELERATION 1.40
POWER RECORD
PRESSURE AT MOTOR
SPEED—TIME CURVE
ACCELERATION TO
SECONDS

FIG. 2.

lower or materially higher than the speed illustrated in the diagram of the typical run. It is interesting to note that the formulas of Davis, Lundie, and Smith all indicate a train friction of from 12 to 13 lb. per ton at a speed of from 40 to 45 miles per hour. The speaker believes, however, that within the limits of speeds considered by Messrs. Lyford and Smith, the assumption of 13 lb. per ton would give results substantially as satisfactory as those derived from any of the formulas which have been considered.

The speaker calls attention to the fact that while the time-velocity curves shown in the paper which has been presented are so drawn as to indicate a fairly uniform rate of acceleration during the period of rheostatic control, yet this rate is in reality

by no means uniform. To illustrate this, he calls attention to Fig. 2, which has been plotted upon a larger scale in order to show clearly the increments of current, the total loss of current for a period approximating a second in passing from series to parallel, and the resultant relations of the actual speed-time curve and the theoretical speed-time curve. The actual speed-time curve as drawn has been derived from the current and pressure readings, and by calculation from the speed and torque curves of the motors. The speed-time curve as determined by the Boyer speed recorder is also shown. It is to be noted that for an average acceleration of 1.24 miles per hour per second the actual acceleration during a part of the period was as high as 1.62 miles per hour per second. Subsequent to the tests from which the results shown in Fig. 2 have been plotted, marked improvements have been effected by changes in the rheostatic connections; as a result of these changes the loss of current and consequently of acceleration while passing from series to parallel connections can now be avoided.

It is to be noted that the current input and consequently the acceleration can be made more uniform by increasing the number of steps of the rheostatic control, but to do this would involve additional complication of apparatus. Incidentally it might be noted that the ideal rheostat would be something of the nature of a liquid rheostat.

Another point to which the speaker would call attention is the fact that the time-velocity curve during braking is never a straight line, owing to the fact that unless braking pressure be decreased as the speed decreases, its effect in checking speed will increase from the point of brake application to the end of the run. He has found that the relation of the average rate of braking to the maximum rate of braking in cases where brakes were applied at speeds of from 25 to 30 miles an hour was approximately three to four; *e.g.*, the average rate of braking will be 1.5 miles per hour per second when the maximum is two miles per hour per second. Recently one of the air-brake companies has produced a graduated release which operates to decrease the brake pressure as the speed of the train decreases, thus obtaining more nearly uniform rate of braking during the entire period of brake application.

Another point to which the speaker believes attention has not been called is the fact that the weight available for adhesion upon the forward and rear axles of a truck equipped with two motors is not equal. This results from the fact that the tractive effort due to the motors is exerted on a line passing through the centers of the two axles, while the resistance due to inertia of the car body is applied to the truck through the king-bolt at a point which in the case of the trucks adopted for the Subway is nearly 12 inches above the horizontal line through the axle centers. Figs. 3 and 4 show diagramatically the relations of the forces involved. It is to be noted upon examina-

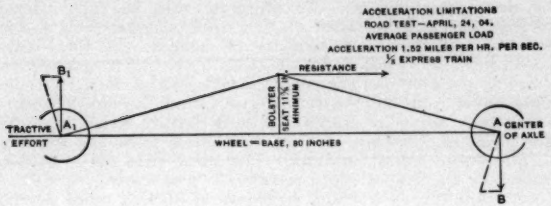


FIG. 3.

$$A\,B = A_1 B_1 = T\,E\,\frac{11.375}{2\times 40} = 0.142\,T\,E$$

Data. 2-Car Test Train. 2 Motors.

Weight of Motor Car,	39.16 tons.
" " Trail Car,	20.14 "
" " Test Train,	59.30 "
" on Motor Truck,	48 885 lb.
Fly-Wheel Effect per Motor,	3.83 tons.
Theoretical Acceleration $T\,E$	20.5%
Maximum $T\,E$ 12 550 lb. —	25.7%

Corrected Fig. 3.

Weight on Rear Axle, 26 226 lb. — $T\,E$ 23.9%
" " Front Axle, 22 658 lb. — $T\,E$ 27.7%

Additional Correction Fig. 4.

Weight on Rear Axle, 25 649 lb. — $T\,E$ 24.4%
" " Front Axle, 23 235 lb. — $T\,E$ 27.0%

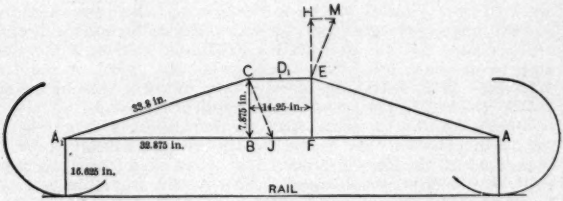


FIG. 4.

$$\text{Vertical force at } C = \frac{T\,E}{2} \times \frac{16.625}{33.8} \times \frac{32.875}{33.8} = 0.239\,T\,E$$

$$\text{Vertical force at } A_1 = \frac{0.239\,T\,E \times 14.25}{80} = 0.046\,T\,E$$

tion of the figures referred to that the resulting tendency to tip the truck, reducing weight effective for adhesion in the case of the front wheels and increasing it in the case of the rear wheels, is quantitatively of considerable importance. It is interesting to note also that this tendency to tip the truck is opposed to, and to some extent neutralized by, the fact that the force with which the motor fields revolve in the same direction as their armatures tends to tip the transom, and consequently the truck, in the opposite direction. Taking both of these tendencies into account, it appears that in a certain case for which calculations have been carefully made the weight upon the rear axle effective for adhesion exceeds the effective weight upon the front axle by more than 10 per cent.

It is apparent in the paper of Messrs. Lyford and Smith that in making their plans they have kept in mind the power supply with due regard to the fact that high accelerations cause great fluctuation of power demand on sub-stations and power plant. Probably that is one reason why they have been content to limit the acceleration to a little more than one mile per hour per second. Obviously, this could be increased at a future time by increasing the motive power equipment and by reinforcing the power supply. It seems to the speaker that the time will come when such increase would be desirable, because one of the things which should not be forgotten is the fact that the more important side of the account in a railway project of this kind is the earning power of the property and this is obviously increased rapidly by higher speed in service.

C. O. MAILLOUX: When he first looked the paper over, the speaker was led to expect important new disclosures of simple methods of predetermination in handling electric traction problems. In that respect, his expectations were not fully realized. So far as methods of procedure are concerned, he found little, if anything, that is not already known to and practiced by every engineer who has had to deal with similar problems. He experienced a sensation of relief, however, when he discovered that the most valuable lesson taught by this paper, was that the theoretical methods, which the authors apparently disparage, even though they still have to use them, are capable of giving results which differ from those obtained in actual tests by only a few per cent. This appeared to him to be all the more remarkable when the theoretical method was presumably handicapped to some extent by simplifications, made to save tedious calculation.

In reference to the discrepancy between theory and practice, Mr. A. H. Armstrong had told the speaker more than three years ago that the predeterminations of the energy consumption, in watt-hours per ton-mile, when made by reference to hypothetical "typical" service runs, assuming the line to be level and to have no curves, came close enough to the results found in actual working to be considered sufficiently

reliable and satisfactory for first approximations, except in special unusual cases. The authors themselves, he observed, are careful to make an exception of the cases presenting unusual conditions.

Some of these unusual cases are apt to occur in any problem, and this method is then absolutely unsafe and unreliable. As an illustration he mentioned the case where the run includes several acceleration cycles, or where there are curves of such sharp radius between the stops that it is necessary to apply the brakes, and to take off the current, and to accelerate again after the curve has been passed. In such cases it will be found that the watt-hours per ton-mile, calculated from a "typical" service run, are very much lower than what actual practice will show. There is also another case, perhaps of the contrary kind, where there is a down grade and an up grade, forming a "hollow," on the middle of the run. In that case one might possibly find just the contrary result, because the momentum acquired while running on the down grade will be partly utilized in running on the up grade, and the time during which current has to be applied may be shorter; and the energy consumption will then be a little lower per ton mile than the theoretical run would show.

The confirmation of theory by practice, which is shown in the paper, must be gratifying to every consulting engineer. Having had and still having the feeling that our theoretical methods are really crude and incomplete and are in great need of development and correction, he felt grateful to the authors for their having taken pains to gather and to present the very interesting additional data contained in their paper which corroborate theory so satisfactorily, even in its present incomplete and imperfect state.

The most novel feature of the paper was the new formula for train resistance proposed under the name of the "Smith" formula. On page 157 of Mr. W. C. Gottshall's "Railway Economics," reference is made to a so-called "tentative or provisional formula," suggested by the speaker. As stated in that book, this formula resembles, in mathematical form, the formulas of Davis and of Wellington, although it gives results which are quite different. It is, like these formulas, and also like that of Mr. Smith, of the general form $f = A + B\,V + C\,V^2$. The third term in such formulas which, as we note, expresses the portion of the train resistance that is due to air-friction, is, in the case of his formula, based wholly on the celebrated laboratory experiments of Professor W. F. M. Goss, made at Purdue University, some years ago, with small car models enclosed in a conduit and subjected to the action of a rapidly moving current of air. Moreover, the first term in this formula, instead of being constant, varies with the weight per axle and with the condition of the track. The formula takes the general form

$$f = \left(\frac{A}{\sqrt{W}} + g\right) + 0.15\,V + \frac{(0.02\,N + 0.25)}{N\,W}$$

in which,

A = a constant depending upon and varying with the diameter of car wheels and journals, its value ranging between 6 and 9.

g = a constant depending upon the condition of the track. Its value varies between 2 and 5 for *first-class track*.

W = the total weight per car in tons of 2000 pounds.

N = number of cars per train.

The reason why the first term was made more complex was that he was trying to find a formula having a greater range of usefulness which would apply to city lines and interurban lines, especially lines with poor track or with grooved rails, or dirty rails. He found there was a certain more or less constant element in such cases or an increase in the resistance, due to the rail itself. This fact had already been noted by others, particularly Doctor P. H. Dudley, the celebrated specialist in track construction. With this formula, by applying suitable values to the constant g (which may be taken at any value between 2 and 15 if necessary), one may get a very high value for the train resistance even for the lowest speeds. In fact, one may, with this formula thus applied, at speeds of a few miles per hour, obtain values of 8, 10, or 15, or even more, lb. per ton for single light cars, which we know is much more nearly what is obtained on cars running on grooved rails, especially when the grooves are filled with dust. His "proposed" formula has, in that respect, a certain advantage over all others.

He quoted from page 157 of the work just mentioned: "For approximate calculations corresponding to average conditions, in the case of eight-wheel cars, the formula could take the following simplified form:

$$f = 3.5 + 0.15\,V + \frac{(0.02\,N + 0.25)}{W}\,V^2$$

The formula referred to was made public in lectures at Lehigh University in April and May, 1903.

Being naturally curious to know how this formula compared with the Smith formula, he took one of the curve sheets, used at these lectures, on which several train resistance curves are plotted according to various formulas, including his "tentative" formula; the example illustrated on this sheet being the case of a train of five 45-ton cars. The results were so interesting as to induce him to present them. On plotting on this sheet, in dotted lines, the curve obtained by the Smith formula, taking $A = 110$ sq. ft. as is done by Mr. Davis, for cars of 45 tons, he found that the curve obtained with his own formula which is marked "proposed" on the curve sheet, comes very close to the Smith curve.

In the case of 45-ton cars, of rapid-transit type, his formula, after clearing fractions, takes the form $2.7 + 0.15\,V + 0.00156\,V^2$ for a train of five cars.

COMPARISON OF TRAIN-RESISTANCE FORMULAS.

Speed miles per hour	Value of Train Resistance by Smith Formula $(3+.167\,V+0.001223\,V^2)$	Value of Train Resistance by Goss-Mailloux Formula $(2.7+.15\,V+0.00156\,V^2)$	Difference
10	4.79	4.36	+0.43
20	6.83	6.32	+0.51
30	9.11	8.60	+0.51
40	11.64	11.12	+0.44
50	14.41	14.10	+0.31
60	17.43	17.31	+0.12
70	20.69	20.84	—0.15
80	24.20	24.68	—0.46
90	27.16	28.83	—0.87
100	31.6	33.31	—1.73

A comparison of the curves and of the calculated values shows in the case of a five-car train, that the two curves come very close (Fig. 5.) The Smith formula gives results which are slightly

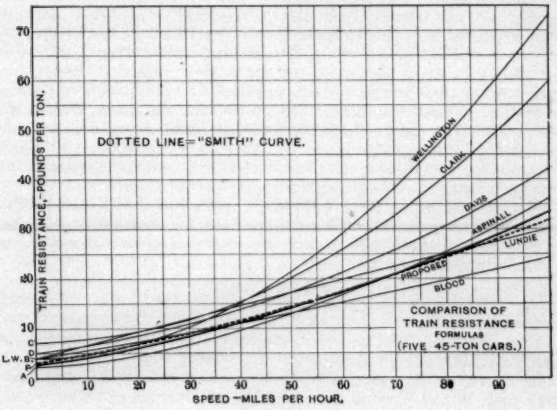


FIG. 5.

higher at low speeds, which are coincident at about 70 miles per hour, and which are slightly lower at higher speeds. The approach of the two curves to each other, in this case, is remarkable. In the case of a single car of light weight (25 tons) which represents an extreme condition, the discrepancy between the two formulas is somewhat greater. The Smith formula then gives results which are much lower at higher speeds, so that for higher speeds, the " proposed " curve, based on his formula, would pass about midway between the Smith and Davis curves.

The speaker believed that a formula built as his was, "from the ground up," entirely on hypotheses and assumptions, is, to some extent, vindicated and possibly justified when we find that it comes so near to "one which gives results close to actual practice" as the authors say of the Smith formula. Nevertheless, he preferred to retain the same conservative attitude which he had had from the beginning in regard to his own formula, and to continue to characterize it as merely "tentative or provisional," as being suitable and convenient, perhaps, for approximative calculations, possibly quite accurate in certain specific cases, but undoubtedly subject to revision and rejection, ultimately. He had made a somewhat close and careful study of the subject of train resistance, more especially during the last two years, in preparing lectures delivered at various times and places on that subject; and the more he studied it, the more skeptical he become in regard to the reliability or value of any formula offered as a universal solution, covering all cases.

Mr. J. A. F. Aspinall, in his celebrated paper on train resistance, which is in many respects the most complete presentation of the subject, read and discussed before the Institute of Civil Engineers in November, 1901, gives a list of 55 train-resistance formulas, including five of his own. Since reading this paper, the speaker had come across dozens of other formulas which are not in his list. It may be said of many of them that they "give results close to actual practice" in some specific case, at some particular speed, with a certain kind or length of train, or under other peculiar conditions; but not one of them, so far as he knew, fits all cases, even approximately, as becomes painfully evident when one sees the way in which the curves wander over the curve sheet when plotted together on the same sheet and according to the same scale. In his opinion, train resistance is one of the details of electric railroad engineering of which we have the least knowledge, and, unfortunately, one on which we need the most light. He expressed this opinion strongly in a letter written last April to Professor H. H. Norris, Supt. of Tests for the Railway Test Commission at the St. Louis Exposition. He quoted from this letter a portion which he considered almost as pertinent to the discussion of this paper as if it had been written for this special purpose:

"The more perfect the apparatus that can be devised for making graphical records of all kinds, the more complete and the more valuable will be the results of the tests made; for, these results if published, can be made available in such manner as to be of the greatest utility, later on, to others engaged in studying various details of the theory and practice of electric train movement. . . . . one of the most important problems now before the railroad engineers is that of finding a formula, either rational or empirical, for *train resistance*. . . . . . if the Railway Test Commission did absolutely nothing

more than to solve this mystery, it would well nigh immortalize itself; failing to do this, if it could render us the important service of eliminating say 50 or 60 per cent. of 200 or more train resistance formulas now disseminated in the railroad engineering literature, it would still have done good and valuable work. Knowledge, in this case, consists just as much in eliminating and blotting out what is obsolete, useless and misleading, as in discovering and adding something new and unknown. . . The ideal thing, of course, is to do both."

He was glad to learn from Professor Norris, recently, that his suggestions have borne fruit and that special tests are in progress at the present time, with the special object of throwing additional light upon that still obscure point—atmospheric resistance—which is the *bete noire* of all train resistance formulas, though it is not by any means the only point on which we need to be further enlightened. The most "popular" formulas, we must not forget, still ignore "starting friction" as if it did not exist. We know, however, from the results of actual tests as well as from theoretical considerations of the laws of friction, that it *does* exist, and that train resistance is relatively high at very low speeds, or at the instant when the train begins to move, and that it then decreases quickly to a minimum value which occurs at a certain relatively low speed, after which it increases again more slowly. The discrepances which are observed in the early portions of the acceleration curves, between the so-called theoretical curves, and the curves derived from tests, are partly due, and perhaps in some cases largely if not wholly due, to the existence of starting friction, which is absolutely ignored in making the theoretical curves. This means that the curve of train resistance, plotted as a function of the speed, is really a "two-branch" curve; this fact is admitted and shown graphically by certain authors, including Wellington, Aspinall, and Dennis; yet all "our" formulas, as well as theirs, neglect entirely the first branch, showing the starting friction. That is why he could not help regarding them all, including Mr. Smith's and his own, as mere makeshifts. He desired to point out that it would be necessary to do something more than merely to devise and introduce a new set of constants in a Maclaurin series of the form $Y = A + B X + C X^2 +$ etc. in order to accomplish something representing a material advance in our methods of dealing with train resistance in railroad engineering. We already have too many formulas of that kind. Moreover, it was not difficult to foresee that the physicist and the mathematician will probably contribute at least as much as—and perhaps much more than—the engineer, to the solution of the problem of finding a general formula for train resistance—if one be ever found. There is valuable work to be done by the engineer in obtaining data for theoretical analysis and in making tests for the purpose of proving or disproving theory.

A very interesting, and perhaps the most amusing thing to him, in this paper, was the cynical commentary of the authors on his own paper of June, 1902, which is characterized as being "scholarly and somewhat bewildering," with the hint added that its value is principally, if not wholly, "academic." He was sure that he did not deserve the implied compliment in the words "scholarly" or "academic" with which the rest of the comment is sugar-coated. There was some humor there and he did not think that the joke was altogether on him. At the time the paper was presented, certain "academicians" thought it altogether too "elementary," and, indeed, considered it anything but "academic." It is some consolation to know, under the circumstances, that requests are still coming from all sides and from many countries, for copies of the reprint of this paper, although no copies are available. He found gratifying evidence in Europe this summer, that this same paper, so far from being regarded either as bewildering or academic, was used as a practical hand-book. He found equally gratifying evidence that the work was also appreciated in this country, in the scores of letters received from American engineers during the last two years. He read extracts from some of these letters.

One of these letters, dated December 3, 1902, was from an electrical engineer who stated that he had "found this paper exceedingly interesting," and particularly so, because he had "recently carried out a similar series of calculations for the Manhattan Elevated Co." He added: "Had your paper been in my possession at that time, it would have been of great value to me in this work, and I am sure that this paper will become a hand-book of great value to all who are engaged in work of this nature." Another letter, received from "8 Bridge Street," New York, under date of December 29, 1902, contained a request for two more copies of the reprint of the paper on "Speed-Time Curves" stating that the first copy was practically worn out from having been used "a very great deal." The third letter, acknowledging receipt of the two letters in question, said:

"As I wrote you the other day, I have already had occasion to make use of these and have found them of great service to me in various railway problems. I most heartily concur with the expressions that I have heard from many engineers that this presentation of the subject is the most exhaustive and thorough that has ever been attempted."

The speaker thought that further evidence on this point was unnecessary.

His paper was intended to cover only one detail of the art of predetermination in electric traction problems—the plotting of speed-time curves. It merely sought to present means whereby an approximative calculation or even a "guess," in regard to the equipment required for a given electric railroad service, could be tested or analyzed, with more or less precision, ac-

cording to the importance of the case. He did not, at that time, and did not, at the present time, take the position that either this method or any other theoretical method known to him can be followed with confidence or safety, without the exercise of some judgment. It was very natural, therefore, that he should concur fully with the authors in the opinion expressed on page 692 that "important details are frequently settled by quite simple processes of reasoning." The paragraphs (a to f) on pp. 692 and 693 might, almost be characterized as "axioms," for they are so self-evident as to require no demonstration or argument. Every engineer using a little common sense, would, he thought, do these things naturally, as a matter of course. He could not believe that any engineer having had even a little experience in any kind of work, would neglect to canvass the situation thoroughly at the outset, so as to ascertain the requirements of the case, or that he would fail to consider the possibilities as well as the limitations created by them and also to appreciate the extent to which they influence the character of the equipment, in a given case. In all the cases that have come to his knowledge the process recommended by the authors was substantially that followed. In almost every case he had found certain features or requirements which decide and settle some point in a peremptory manner, rendering discussion or analysis not only useless but even ridiculous. It usually needs but very little study, and very little calculation, if any, to ascertain the limits between which the choice of motors must be made, and even to narrow these limits until one knows that the choice lies between two or three sizes only.

Answering one of the questions propounded on page 695; viz., how much of this tedious calculating is necessary? He should say, simply, "*just what and only what cannot be avoided*." His experience showed that the "amount" of calculating and its "tediousness" both depend greatly on the man who is doing the calculating.

To take one extreme case, a person who is totally inexperienced, even though competent technically, might have to make the "tedious calculations" an almost endless number of times, for innumerable hypothetical cases, based on as many kinds of equipment, and yet he might not be able to avoid making a serious mistake. To take another extreme case, an engineer having had wide experience with very similar or perhaps almost identical cases, and having good judgment, might see and might be able to give "offhand" without any calculating whatever, the best solution of the problem. He may have, from experience, from data, and from statistics in his possession, his intelligence, etc., that ability to grasp and "size up" the situation which make the case both clear and simple to him and enables him to do by intuition, let us say "guess," if we prefer, what others could not accomplish even with the most comprehensive

calculations. Between these two extremes, there are almost as many cases as there are kinds of men; but, after all, they all proceed by substantially the same process, within their limitations of intellectual equipment, knowledge, and experience. That process is essentially *empirical*, when it can not be *rational*; and in this case, it can not *become* rational until the *theory* has been further developed, *no matter by what means*. To put it in simple plain language, that process is simply this: "*look the case over carefully; take up what you 'figure out,' what you 'guess,' or what you 'hope' or presume* (either from your knowledge or experience, or that of others), *will best suit it; and then use the best means at your command to ascertain how nearly or how badly it fits; and if, at first, you don't succeed, 'try, try again.'*" If he understood the authors, this description also covered their method of procedure fairly well. He had had to do this repeatedly in cases where the path was unbeaten and uncertain, as it is in analyzing problems in electric traction. So have, doubtless, many others. But he had, each time, done it from necessity, from want of a better way, more than from choice. He realized that there *ought* to be a more direct way, a more *rational way*; and when once that rational way was accessible, he followed it.

He had no greater fondness for tedious calculation than the average engineer. At the same time, he did not believe that it should be shirked so long as it can accomplish a useful purpose. The "limit," in this case, depends largely on the *thoroughness* with which the engineer is accustomed to do his calculating and the *degree of precision* with which he can *content* himself. He knew a *few* engineers who are, perhaps, open to criticism for *excess* of precision in their work; but he also knew *many*, indeed *very many*, who are too much open to criticism for exactly the opposite reason.

He greatly favored and gladly welcomed any new developments in methods of predetermination, whereby the work is simplified. He probably disagreed with most of the others, however, in stating that he anticipated more progress in methods from the *theoretical* than from the *practical* side. He said this, bearing in mind the great value of the statistical method in furnishing clues and short cuts whereby a desired result can be obtained, or whereby the possibilities can be ascertained in a much more simple and direct manner. The very excellent paper by Mr. A. H. Armstrong, on the "heating of railway motors," read before the INSTITUTE, was a magnificent example of the manner in which statistics furnish clues to newer and simpler methods; but such papers and presentations of statistics or the conclusions based upon them, do so merely to the extent that they simplify, develop, perfect or correct *theory*.

In conclusion, he recalled some remarks made by him at the Niagara Falls convention, in the discussion of Mr. F. W. Carter's paper on predeterminations in railroad work, which

show that he did not believe specially in plotting speed-time curves for a pastime, even though he were the author of an "academic" paper on that subject. He quoted, emphasizing a few words: "Consequently, it is not enough to have a means of *readily plotting* speed-time curves. We want more than a means of readily plotting the *subsidiary curves*,—we want means of *obviating* the plotting of them, and of obtaining, nevertheless, the *results which they would give us*, and which we now have to obtain by plotting them and laboriously integrating them by mechanical methods." The thought in his mind, at the time he said this, was that these curves, including the speed-time curve itself, though desirable for graphically *picturing* the results, are not necessarily indispensable as instruments or means for *obtaining* these results in the first place. He already had this thought even at the time his paper was read, as the discussion shows.

He believed this now just as fully as he did two years ago. Indeed, he believed this now even more fully than he did when he said it, because he had since that time made some progress of a satisfactory character in that direction, the results of which will be made public in due time.

H. WARD LEONARD: The title of the paper of the evening is "Heavy Electric Traction." The speaker's remarks will bear more on what might be termed Heaviest Electric Traction. As the title of the paper seems to make it proper, the speaker would like to touch upon the subject of operation of the heaviest electric traction, and bring out some figures which have been obtained from various sources, and should prove of interest.

One of the points upon which electrical engineers would like information in considering the possibilities of trunk line electric traction, is the power required. The speaker has arrived at an approximate average figure for this of about 125 h.p. per mile of line. This has been obtained by taking the total maximum horse power of the steam locomotives and the total mileage of the railroad systems.

In the case of the Pennsylvania road, the figure is in the neighborhood of 550 h.p. per mile of line, and in the case of a few roads which have very heavy freight service, such as the Pittsburg & Lake Erie, and the Bessemer & Lake Erie, rough estimates show as high as 1000 h.p. per mile.

The steam locomotive of the latest type and largest power costs with its tender about 5c. per lb., but when the weight upon the drivers only is considered, the cost figures 9c. per lb Now with the price per lb., which has been reached in electric generators, as a basis of calculation, it is reasonable to suppose in the case of the heaviest electric locomotives, where the horse power will be relatively low compared with the weight, that they can be made to sell for less than 9c. per lb. on drivers when they have been brought to standard types.

The speaker thinks that the question of the application of

the electric locomotive is one which is largely dependent on the horse power per mile of steam service which it can replace, and that in cases where 250 h.p. per mile of line is employed, the electric locomotive can replace the steam locomotive with a very decided economy. In this connection it will be of interest to state that in the case of the many modern types of freight locomotives, the cost of maintenance per mile run is as much as the cost of the fuel per mile run. This, at first sight, seems almost impossible, but it is a fact that $3500 per annum is the cost of fuel, and $3500 per annum is the cost of maintenance for locomotives of the heaviest type, such as the 2–10–2 type of the Santa Fé locomotives.

Referring to some of the comments which have been made about short and ready methods of reaching approximate results, the speaker uses one which perhaps may be useful in calculating the horse power at the draw-bar: Multiply the miles per hour at which the train is moving by the pull in pounds at the draw-bar and double that product; this will equal the watts. This is correct within a very small fraction. Striking off the three right-hand figures gives the kilowatts, and by increasing the last result by one-third, the horse power is given. For example, a locomotive of 30 000-lb. draw-bar pull running at 20 miles an hour, gives 1200 kw. or 1600 h.p. at the draw-bar.

The speaker wishes to draw attention to the fact that this paper, and the comments which have been made upon it, illustrate the importance of having for heavy electric traction and especially for the *heaviest* electric traction, such methods as will secure the maximum possible draw-bar pull from certain definite horse power and weight on drivers.

It is a fact which most people do not appreciate that a freight locomotive of the most modern type, which will develop 1400 h.p. going at 20 miles an hour on a level, when it comes to the heaviest grade, and its speed falls to six miles an hour, will then be producing in the neighborhood of only 700 h.p. That is just the time when, instead of producing half the horse power that is produced on the level, there is needed a locomotive that will produce three to six times the horse power ordinarily required on the level. In this regard the electric locomotive has important characteristics that a steam locomotive lacks. It has the ability, for the short time required to cover grades a few miles in length, to respond to a very great demand for overload capacity or overload currents without the heating effects accumulating sufficiently to harm it. In the case of heavy grades of 2 and 2.5 per cent. the horse power of the locomotive, necessary to maintain the speed of the train and prevent traffic congestion, is from three to four times the horse power on the level. Three steam locomotives, applied to a train on grades of this character, do not produce more than one and one-half times the horse power that is produced by one of these locomotives on the level. And yet the demand for power is, of course, greatest on grades.

Heretofore in discussing the possible application of electric locomotives to trunk line use, the question has been narrowed down to the consideration as to whether or not fuel can be saved—whether power can be generated at a distant station and transmitted more cheaply to the locomotive than by having independent sources of power in each locomotive. The point has also been much discussed whether or not some labor cost may not be saved in driving the electric locomotive. These points are trivial in connection with this problem. Assuming $100 of receipts for a railway, the fuel cost represented in the earning of that $100 is between seven and eight per cent. The total cost of everything which can be charged up against the power, including the shops and everything of that kind, will not run as high as 20 per cent. Given a road where the movement of freight is pressing, and the road is demanding more locomotives to haul the traffic, it is evident that if there can be applied to the train twice the horse power now obtained from steam locomotives the receipts can, in a given length of time, be doubled and at a comparatively slight additional expense.

W. S. FRANKLIN: It seems to the speaker that in a matter like this—of the relation between train speed and train friction—in which there is the element of chance, that one of the most important things to be found out in tests is what one might call the *probable variation* (analogous to probable error of a measurement, only here it is not an error but an actual variation of the thing measured).

To make the thing more definite, the speaker thinks that there is an important element of reality in what many of you are pleased to call the discrepancy among these various curves of train friction. There is no theoretical relationship between friction and speed; and there can be no ultimate theoretical solution of this problem. There is too great an element of chance involved. Strictly speaking, it is a matter which depends upon the conjunction of an infinite number of fortuitous elements, and such a problem cannot be rigorously formulated.

The speaker suggests that one of the most important practical results from a set of tests would be the establishment of the *probable variation* of friction in different runs, so that the designer of a car equipment would know the factor of safety to allow in choosing the motor to be used in order to make provision for the probable discrepancy between the calculated amount of power—the actual mean amount of power observed during the many runs of the test—and the actual amount of power likely to be consumed in a series of runs in service.

In a test involving many individual runs, not only should the mean be taken and used as an engineering datum, but also due attention should be paid to the discrepancies, and these discrepancies should be formulated by the laws of probabilities and the result used as an important engineering datum.

The discrepancy among different friction speed curves, in so far as these curves do not go beyond the limits of the observations upon which the curves are based, must be ascribed to chance except in so far as the different conditions are specifiable under which the observations are made. The speaker doubts very much whether any full specification of this kind could be made. He is inclined to look upon the discrepancies of these curves as largely fortuitous. You will note indeed that these discrepancies are slight in the observed parts of the curves. The exterpolated parts of the curves are absolutely meaningless.

A. H. ARMSTRONG: In looking over this paper it is noted that two thirds of it is devoted to discussing two train formulas, one devised by one of the authors and the other by Mr. Davis. It is not the intention in taking up the discussion to determine whether the formula devised by Mr. Davis or by Mr. Smith, or the indiscretion perpetrated by Mr. Mailloux two years ago and admitted by him a few minutes since, is correct. But an attempt will be made to prove that given any formula of reasonable accuracy, holding true for speeds up to 40 miles an hour, it would be impossible with careful and accurate calculations to arrive at the results noted in this paper.

Turning first to page 704, there is given in Figs. 7 and 8, in full lines, a reproduction of some speed-time curves taken at Schenectady, and in dotted lines the calculated results of the Davis and Smith formulas. Referring to Fig. 8, two things are noted, one of which is that the 670 amperes does not agree with the 42 miles an hour with the equipment cited when running at 570 volts. The actual speed given with this current, according to the speed-torque curves of the motor is 38.8 miles, or, in other words, it practically duplicates the Davis curve given on the previous page. To get a speed of 42 miles at 570 volts requires a minimum input of 600 amperes, or 70 amperes less than that given in the curve. Any calculations given here are open to some criticism, as they were made while coming down from Schenectady on a train running at 60 miles an hour; and those who have worked a slide rule under like conditions know the difficulty of arriving at accurate results. Referring to Fig. 7, the minimum current is given as about 720 amperes, and corresponds very closely to the actual speed; but it must be pointed out that the better showing of the Smith formula, on curve Fig. 8, is not due to the somewhat lower friction of 2.5 lb. per ton at 40 miles an hour, but to the inconsistent method of calculating the two curves. For instance, in Fig. 7, the current represents a constant rate of 720 amperes, while the time-speed curve still shows an increasing speed for at least 40 seconds during the latter part of the time the power is applied, and gives results which are somewhat inconsistent.

In dealing with the speed-time curves given in this paper, two or three sources of inaccuracy are present which perhaps have not been fully taken account of by the authors. The

first three sets of curves are stated to be plotted from readings taken every five seconds by the observers watching a more or less dead-beat ammeter. The Arnold-Potter tests were taken with two-second readings, with one man reading, another jotting down the results, and a second group of observers reading maximum and minimum current values and time at which they occurred in order to arrive at the rheostatic peaks. Even with the precautions taken in the Arnold-Potter tests, wattmeter readings show that the product of volts and amperes was from 5 to 10 per cent. below the carefully calibrated wattmeter results. What the results would have been with five-second instead of two-second readings is open to a good deal of comment, and the curves in Figs. 2 and 3 cannot be looked upon as forming a very accurate basis with which to compare calculated results. Referring to Fig. 4 it is noted that three results are compared, one tested and two calculated, with very different braking rates. No obvious reason is given for the rates being different, and the effect of the more rapid braking rate is equally apparent as a more rapid accelerating rate, so that the theoretical value of the Smith formula plotted to the maximum braking rate would give a somewhat lower energy input. The 94 watt-hours per ton-mile given would drop below that figure and show a still greater discrepancy with the test value of 99 watt-hours if the more rapid braking were used for all three curves.

Referring to Fig. 5, it is not apparent why the authors should have allowed the calculated run in dotted lines to fall so far below the actual acceleration observed in the test run, while on the next page in comparing the Smith formula the actually observed acceleration rate is closely followed. The effect of using a lower rate of acceleration with the Davis curve is to cut out any coasting and thereby to increase considerably the watt-hours per ton-mile, not on account of the small increased pounds per ton friction, but due to the absence of coasting. On Fig. 6 it is found that the Smith formula enables the run to be made in some five seconds less than the actual test run, giving a calculated value of 72 watt-hours as compared with 79.4 by wattmeter in the test. If the time had been increased to the 136 odd seconds of the test run, the 72 watt-hours would still further be reduced by the introduction of more coasting. so that as an estimate the comparison would be for 66 or 68 watt-hours calculated against 79.4 by wattmeter, a result which is not very close even for an approximation.

On Fig. 9, page 706, it is noted that the theoretical calculated energy consumption of the train is some 10 per cent. higher than the test results, although the dotted line shown is at a lower friction rate than the test value; in other words, the formula used gave a lower friction value than was obtained in the test, but the calculated watt-hours per ton-mile were greater. which is inconsistent. On the next page, Fig. 10, the dotted

line and full line show practically the same coasting curve, following very closely, and yet the calculated energy consumption is 83 watt-hours per ton-mile, against 77 in the test; and this obtains also with the higher average acceleration rate of the calculated curve. We should naturally expect that with the same friction rate, which is the only undetermined factor entering into the calculation of the speed-time curve, that the result would have been much closer than that given.

Passing on to page 711, it says, " It is safe to assume that a check made on the comparative determinations for square root of mean square current will indicate the correctness of the assumptions for the determination of the other requirements." The impression obtained by reading this page and others following is that the chief object in developing a series of speed-time curves was to obtain the square root of the mean square current, and that this current value was the controlling factor entering into the selection of the proper motor for the work. The details of the old controversy of the proper method of obtaining the capacity of railway motors will not be entered into here other than to state that the square root of the mean square current is ordinarily used in calculating the copper losses only of the motor. It ignores entirely the core losses of the armature and field and is not applicable to any other type of motor than the direct-current motor. It can not be used with the single-phase alternating-current motor, and furthermore excludes the brush-friction losses, the bearing losses, and all internal losses of the motor other than those depending on the current itself. Furthermore, the core losses and other incidental losses are not a direct function of the current employed; that is, with a given cycle, a certain relation may exist between the total losses and the square root of mean square current, and in that way the square root of mean square current may be used as a basis of the motor heating. In another cycle an entirely different ratio may exist; and any motor-heating predeterminations based solely upon the square root of the mean square current would fall through as being inaccurate and misleading if applied to general railway problems.

In connection with this a new factor may be mentioned which enters into the determination of motor capacity, which has been brought into prominence by the introduction of the single-phase railway motor. In direct-current motors it was thought when the copper, core, and brush-contact losses had been obtained that approximately all the internal losses of the motor had been noted; so it was put down that the total losses in the motor were those losses enumerated, plus a certain value for brush friction. In developing the single-phase motor with the 150 volts or so on the commutator which is incidental to such motors, the experiments encountered a brush friction fully three times as great as in the 600-volt direct-current motor, there being something like 1500 watts total loss in the motor

tested which had never been counted on. The first motor that was built, in which no especial attention was paid to the brush-friction loss when mounted on a car and hauled as a trailer with no current whatever in the armature, would heat unduly due to the brush friction alone. That test was followed up by a series of experiments and improvements looking to a considerable reduction of this brush-friction loss until now it is within reasonable limits. This instance is cited to point out that the square root of mean square current is not a true criterion of the motor heating in service and that all the losses—not only the actual losses, but their subdivision and relation to each other—must be carefully determined before a proper motor can be selected for a given piece of work.

The authors have indicated their desire for some short-cut method that will avoid the laborious calculations involved in the preparation of speed-time curves in detail, but the approximate methods used indicate a lack of accuracy in the results obtained, making it an open question whether the careful preparation of speed-time curves is not necessary. No one appreciates the tedious nature of such calculations more than the speaker; but no rational method has yet been proposed which will do away with the necessity of such calculations for final results in the selection of train schedules and motor equipments. Not only is it necessary to calculate speed-time curves under the conditions imposed, but also to plot other curves with a modification of some of the conditions in order to determine the amount of leeway a given equipment possesses on either side of the limitations imposed by the specific problem in hand. General curves worked out throughout the range of limitations of rate of acceleration and braking and train friction will give reasonably accurate approximations to serve as a basis for detailed calculations, which must be gone through with in detail in order to get accurate results. Such accurate results are required, as it is folly to presume that less care should be exercised in the selection of the rolling stock of a road when its value exceeds that of the entire generating station and feeding system.

C. T. HUTCHINSON: The speaker has published two papers on the subject of predetermination of the operation of electric motors in railway service, both of which were based upon the assumption that certain average results could be depended upon for the ordinary type of railway motor in use, and that the results deduced from such averages would be found to correspond substantially with practical results. The principal object of the method proposed was to eliminate the tedious plotting of speed-time curves, and to outline a general method applicable to any motor to predetermine the temperature rise of a particular motor under service conditions. The paper this evening gives the speaker an opportunity to apply his method to some of the results given. The motor on which these results are based

is the Westinghouse No. 86 motor, which has been tested more elaborately by Mr. Stillwell and his assistants in the Interborough Company. Through the kindness of Mr. Stillwell the speaker has had access to the results of these tests. The method proposed by the speaker, substituting the constants of this particular motor, is the basis of the statements that follow.

The speed-torque curves of this motor were first compared with the average speed-torque curves assumed in the papers referred to, and were found to be in practical agreement. The method proposed was then applied to the run shown on Fig. 1, using the Smith formula. The energy per ton-mile, as calculated by this method, came out 46 watt-hours; the result given by the authors of the Smith formula is 48.8 watt-hours,—a practical agreement. This result was obtained by a calculation taking probably five minutes, and should be compared with the time necessary to plot and integrate the speed-time curves shown in Fig. 1.

The method was then applied to a comparison of predicted and observed results in the typical local run of the Interborough service. This is the run shown in Figs. 9 and 10 of the paper. The energy per ton-mile calculated by this method was 75 watt-hours; the test results show an average of about 78; this agreement is as close as could be expected.

The most important matter to predetermine is, however, not the energy requirement, but the temperature elevation of the motor for any given run. This can be only predicted when the temperature that the motor attains, under approximately similar conditions, for a given energy loss is, known,—that is, when the radiation coefficient of the motor is known. The only way to determine this coefficient is by test. The speaker's method assumes that such test has been made, and that the value of this coefficient under different conditions is known. The temperature elevation of the motor will then be determined by the heat loss in the motor during the run. Hence if the average heat loss in the motor, as calculated, agrees with that shown by test, the temperature elevation will also agree. Applying this method, then, to the data of the typical local run of the Interborough system, and using the test records kindly furnished by Mr. Stillwell, the calculated core loss is 3360 watts; the test results give an average loss of 3460; the agreement is substantially exact, and therefore the temperature elevation predicted by the method in question would have been practically exact, assuming the radiation coefficient to have been properly determined by tests under the conditions of this run.

The greatest value of a method of this kind lies in calculating the results of a variety of runs, such as given in Tables 2 and 3. Using the method of the authors, the calculation of the results given in Table 2 alone would probably require the work of at least one man for the better part of a week. The speaker has applied his method to the same series of runs, and in less than

an hour has obtained results of the character shown in the tables in question, together with other results giving, as he believes, data of far greater value. These results are, briefly, as follows:

Table 2 gives 17 separate runs and a summary for the round trip. For each trip it gives further the square root of mean square current, both for the actual run and for the typical run; that is, the average of all the separate runs. These figures are given to show that the use of a typical run in place of the separate runs is a justifiable assumption. This, by the way, is also the assumption made by the speaker in the papers referred to. These 17 runs, using curve-sheets already published by the speaker, gave an energy loss per ton-mile for the different runs varying from 60 to 87 watt-hours; multiplying the length of each run by the energy consumption per ton-mile, and taking the weight average, there results a figure of 66 watt-hours per ton-mile as the average of these separate runs. The quantity required for the typical run calculated in the same way is also 66 watt-hours per ton-mile. This result corroborates the result given by the authors, and is a sufficient demonstration that a typical run can be substituted for the individual runs in a case of this kind, with a high degree of accuracy as far as the energy consumption is concerned.

A more important matter is, however, the temperature elevation of the motor. The authors assume the same motor, to be used with the same gearing, etc., for these various runs, and assume the temperatures to which the motor will attain to be practically determined by the value of the square root of the mean square current. Applying the method of the speaker, and choosing an initial acceleration so that the temperature elevation for the type run shall be 75° cent., the temperature elevations for the individual runs will vary from 107° to 71°; the temperature elevation for a composite run, made up as indicated in Table 2, would be slightly greater than 90°. In other words, the substitution of a typical run for the separate runs is sufficiently accurate for the determination of the energy used, but is not satisfactory for the determination of the temperature elevation of motors, and therefore not satisfactory for the determination of the motor capacity, which is, of course, directly dependent upon the temperature elevation.

Speaking generally of the subject, it is the opinion of the speaker that the relative importance of the various phases that have been discussed this evening are somewhat as follows: Train resistance and plotting of speed-time curves of least importance; the determination of energy requirement of next greater importance, but still of slight importance compared to the third point,—that is, the predetermination of temperature elevation and of motor capacity. The third and most important point is practically left out of consideration by the authors of the paper.

W. N. SMITH: Referring to the interesting point brought out

by Mr. Stillwell in regard to adhesion during acceleration, which hitherto seems to have been overlooked, the speaker would recall to the attention of the INSTITUTE the interesting paper on braking contributed about two years ago by Mr. R. A. Parke, which shows how the converse of Mr. Stillwell's proposition holds true in a car truck when the brakes are applied.

As to the discussion of theory versus practice, this paper is not intended to be a statement that theory is of no account and that practice is the only rule to follow. It is not a question of theory versus practice; the paper shows that one bears out the other.

One of the points the authors wish to emphasize is the proper *interpretation* of theory in presenting a question of this kind to busy, hard-headed steam railroad men who have spent their lives in the railroad business and have neither time nor patience to listen to mathematical explanations of the points involved.

Concerning the train resistance formula, the authors do not claim any more for it than Mr. Mailloux or any one else can claim for any formula. It is by no means the last word on train resistance formulas; but the paper shows that it is based on results which are practical, and it certainly compares very favorably with others for the particular conditions of train weight and equipment.

As to the effect of sharp curves and grades, the particular problem here considered has very few curves to deal with which a train could not run around at practically maximum speed. Where they did exist, however, particularly in the case of the North Side Division, their influence on the train runs was carefully examined, as is shown in Part II. of the paper, with the result that the general typical run was found to compare sufficiently well with the actual plotted runs for all practical purposes.

Increased friction at the instant of starting may make a difference, but it is not in evidence in any of the practical test curves exhibited in the paper, nor is it shown in the curves presented by Mr. Stillwell.

Mr. Armstrong's criticism of Fig. 4 is covered by a note which says, " Power cut off at same distance from start. Average speed maintained constant by varying braking rate." Some of his criticisms in regard to the current curves are partly to be explained by the fact that some of the curves have been reproduced half a dozen times since originally made and are a little exaggerated, and in one or two cases are not quite exact. The curves made use of were originally made for the Arnold and Potter paper, and were taken from the TRANSACTIONS, and in this way it is likely that some inaccuracies have arisen which may explain some of the criticisms of Mr. Armstrong.

The authors are disposed to view such problems from the standpoint of the consulting engineer, and in the interest of the customer. Large enterprises of this character are likely to

be handled by consulting engineers rather than designing engineers. It is hardly necessary to say that the consulting engineer cannot be expected to view the merits of any apparatus solely from the standpoint of the designer, because the minutiæ of design do not necessarily appeal to him. The consulting engineer is the interpreter to the customer, of the apparatus and methods advocated by the designing engineer. Whether or not the consulting engineer is interested in all the various intricacies of design which are of particular importance to the designing engineer, he must be able to present general results to his client in a clear, convincing, practical manner which will enable the client to follow the consulting engineer's reasoning and be governed by his conclusions.

Applying this principle to the question of the rating of motors, some of the gentlemen who have discussed the subject have brought into it a large number of the quantities which are taken into their calculations in the design of motors. They expect consulting engineers to follow through the various losses in the motor for various cycles of work, experimentally determining the degrees rise per watt loss, and finally the exact temperature rise for certain duty. While they admit that this process is cumbersome, they do not yet seem to have put forward any simple method of general application which it is reasonable to ask a consulting engineer or his client to follow in detail. Such experiments may be necessary for *designing* engineers and manufacturers, who must make the completest possible study of their apparatus and its possibilities; but when it comes to interpreting the results of such experiments, it is too much to expect that either the consulting engineer or his customer should be obliged to follow out the fine points of a separate laboratory test for every possible condition.

In contradistinction to such methods of arriving at results, satisfactory though they may be to some manufacturers and engineers, there has been developed a simple method of expressing the capacity of railway motors by means of determinations of the root of mean square current and the "equivalent volts" which appertain to any cycle of operation, representing an equivalent continuous load which a motor may safely carry in service without regard to the particular number of degrees temperature rise which may result from it.

It is found in practice that the exact temperature rise of motors in service is appreciably affected by such a slightly different condition as the position of the motor in the car truck. The motor which gets the greatest fanning effect by virtue of its position in the truck may be cooler than one not so favorably situated, by 10 degrees or more. Such results are likely to diminish considerably the value of tests for the exact determination of temperature rise.

Great exactness cannot be claimed for any of the assumptions made in electric railway predeterminations. All the variables

are likely to be several per cent. out of the way; and temperature rise can certainly not be calculated with any greater degree of accuracy than pertains to the initial assumptions.

The method of using the root of mean square current for determining the sizes of electric railway motors, as proposed and demonstrated by Mr. Storer and Mr. Renshaw, has not only proved to be most valuable as a working basis by virtue of its simplicity, but has also proved out in practice remarkably well.

Referring to one of the last speakers, who showed the way in which his theoretical method of deriving results is corroborated, to a great extent, by the presentation in our paper: it seems to the speaker that his theory is now worth considerably more to a practical man than it was before this demonstration was made. His theory is undoubtedly a good one for its purpose, but the one thing to bear in mind is the relative ease with which its correctness can be demonstrated.

Methods that are largely graphical have an additional value in that they are very easily checked, and that arithmetical errors, if made, are found more readily than they would be if such a problem were worked out on the basis of a mathematical analysis requiring sheets of algebraic equations. A train schedule once settled on, and sub-stations, transmission line, and power-house located, a comparatively few days' work will enable a few skilled men to calculate and tabulate in permanent form the rapidly varying loads involved in such a problem, from which the determinations for lines and apparatus can be made at leisure.

E. E. RIES: On referring to curve 17, page 720, it will be seen that the changes in weight of the live load of this particular equipment do not materially affect the speed characteristics of the equipment; in other words, the electric train weighs 70.6 tons with seated load, and 77 tons with the standing load, a little over six tons more. This shows a very large disproportion between the dead weight of the train, and the live load or the passengers carried.

As the standing capacity of the subway cars employed in this test is greater than the seating load, it may be assumed that the total passenger weight in the two-car train referred to was not over 12 tons. This would make the dead weight itself 65 tons, or more than five times in excess of the maximum live or paying load. In other words, it required *only one-sixth* of the total power to transport the full passenger load, *whereas five-sixths of the power is expended in moving the empty train.* We have been accustomed to the waste which has taken place in the steam-engine, and to lay a great deal of stress upon the question of fuel consumption when discussing electric traction problems; now it would seem as if a strenuous endeavor should be made to lighten the excessive weight of the train itself as compared with that of its passengers.

O. S. LYFORD JR.: The paper was not intended to cover all the phases of the engineering necessary in selecting motors for such a project as referred to. Simply a few illustrations are given bearing upon the general points made. There is no desire to disparage the admirable work which has been done along purely theoretical lines, for all such work is of value in helping to reach the last analysis. It was desired simply to correct some impressions which have been given. There is no particular claim made to originality. The literature, as a whole, is lacking in evidence of the character given in the paper. No doubt other members have such data as given, which would be of great interest to the INSTITUTE. Recent proceedings of the INSTITUTE have brought out much practical information regarding transmission line construction, lightning protection, etc.; it is suggested that much information of a similar character regarding experience in electric traction could be furnished and would be of great value. The plans of the Railway Test Commission, if carried out, will add materially to the literature on the subject.

It is gratifying to know that Mr. Mailloux agrees with the authors of the paper that the amount of elaborate calculating to be done should be only that which cannot be safely omitted. It is a question whether we wish to obviate the necessity of plotting speed-time curves. A study of the actual characteristics of these curves is often very instructive. Moreover, the problem is not finished when the motors are selected. The current-time curves have to be studied very carefully in the consideration of sub-station and power-station loads.

With reference to Mr. Armstrong's comments, they are those common to the fine-toothed examination of each other's data frequently indulged in by the manufacturing companies. Irrespective of his adverse analysis the general facts are as given in the paper. The Arnold and Potter tests were made by the General Electric Company and can be analyzed more closely by the General Electric engineers than by the authors. It would be of interest to the INSTITUTE to have a similar comparison of theory and test by those best acquainted with the test data and the motors used. As to Mr. Armstrong's remarks concerning the use of square root of the mean square current in the determination of heating of motors, it may simply be said that this is a method which works fairly well.

WM. MCCLELLAN (by letter): The engineering work in connection with railroad projects is for the purpose of settling three questions: the power-house equipment, the transmission line equipment, and the car equipment. These are in every way complex. For the first we need a daily time-power curve for the whole system; for the second a similar curve for each section of the road, the size of the sections depending on local conditions; and for the third we must consider the sections demanding greatest accelerations and prolonged heavy current supply. As a rule, no type-run will be sufficient to answer

these questions. It is true, that there are some locations (chiefly between the Ohio and Mississippi) where the only variable is the distance between stations, in which type-curves might be serviceable. But in most cases, where the country is more or less rolling, such as we have in the vicinity of Philadelphia, with all kinds of combinations of curves and grades, the type-run would be of little avail.

The question, "How much tedious work is necessary?" presents itself to everyone, and the writer believes that tedious as most of us find it, the theoretical methods will prove the fittest by survival. Certainly the problems set by the electrical engineer are as complex as any set by the civil engineer, with his grades and alignment, and yet every one knows the amount of tedious work he is willing to devote. What we need now is data of all kinds. The engineers of the New York Central found this out soon after they started, and they had to get what they needed. A general method assumes the knowledge of enough data to make such generality possible; and it is for the lack of this data that frequently the theoretical method shows to poor advantage.

In this connection the writer would be interested to know upon what data the derivation of the Smith formula is based. The writer would also be interested in knowing why motor cars alone are absolutely necessary, as is intimated in the early part of the paper. It would seem entirely possible that some locomotives might be used advantageously. Many steam railroad men are now advocating a proper division of the work between motor cars and locomotives. In considering the great advantage of motor trains for much of our railroad work the peculiar field of the locomotive should not be forgotten.

Discussion on "Problems of Heavy Electric Traction," at Pittsburg, Pa., December 5, 1904.

N. W. Storer: It is not the purpose of this discussion to give an exhaustive treatise on the subject announced, but merely to bring forward one or two points that have come up in working over electric railway projects.

The question of an efficient means for regulating the speed of electric motor-driven cars has always been a serious one. The direct-current motor is limited to two running points on the controller—full series and full multiple. On these two points the cars are obliged to meet all the contingencies that arise. The motors must always be geared so as to meet the maximum speed conditions required to maintain the schedule. This necessitates in most equipments used for interurban service, as well as for locomotives, very inefficient operation at the low speeds in the cities and wherever frequent stops are made. There have been various schemes proposed to remedy this, the first being used in the original Sprague motor, where the field was wound with several coils which were successively connected in different combinations which varied the field strength and consequently the speed at which certain torques were developed. This worked successfully on the small motor and was attempted to a certain degree in other double-reduction motors designed by the Thomson-Houston and the Westinghouse Companies. It was followed later by the General Electric motors which were provided with a resistance for shunting the field coils to obtain high speeds. It was found to be unsatisfactory, however, and as far as we know is not now used to any extent on modern motors. The problem still remains, and how great a one it is can hardly be appreciated by one who has not studied it by means of the speed-time-current curves.

It is well known that gearing a motor for 20 miles per hour with a certain tractive effort will take 25 per cent. more power to accelerate at a given rate than if it were geared for 16 miles per hour, and that the motors may easily be overloaded and burned out in performing a certain work, and that the consumption of power is much too great if the gear reduction is too small. This is an evidence of the necessity for a more efficient speed control which should be grasped at once by everybody.

The steam locomotive, it is claimed, has the advantage of the electric railway motor in that it can develop its maximum output over a wide range of speed while the electric motor operating at a certain pressure develops its maximum output at only one speed, and the output decreases rapidly as the speed increases. This renders it practically impossible for the electric motor to make up lost time unless it is geared for a higher speed than is ordinarily required. This again points to the necessity of an efficient means for speed regulation.

Unfortunately there seems to be no means for avoiding the difficulty with 2-motor equipments. With 4-motor equipments,

which are now used a great deal for interurban service, the inefficient starting may be overcome to a certain extent by throwing all motors in series at start. This gives one more running point. It, however, complicates the control apparatus so much that it is seldom used.

The following plan is submitted as one which, while involving some complications, avoids others and will result in a much more efficient and flexible speed control than any at present in

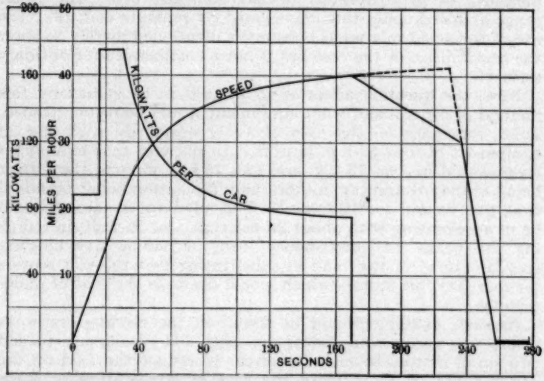


FIG. 1.

Total weight of car loaded—tons	39.5
Length of run—miles	2.2
Schedule speed—miles per hr	28.6
Length of stop—seconds	20
Acceleration—miles per hr. per sec	0.7
Braking rate—miles per hr. per sec	1.5
EQUIPMENT.	
Motors	4–75h.p.
Sq. root mean sq. amperes per motor	41
Sq. root mean sq. kilowatts per car	81
Average kilowatts per car	62
Pressure at car	550

use. It is adapted for use only on cars having at least four axles on which motors may be placed. Briefly, it consists in having two large motors wound for the line pressure and two smaller motors wound for some lower pressure, say 25 per cent. of the line pressure. The smaller motors will be used only in series with the larger ones and will develop a torque in proportion to the pressure for which they are wound. They will be controlled simply as so much resistance and will complicate

the control very little. With these two small motors operated only as motors, the car speeds obtained without resistance in series will correspond to pressures applied to the large motors of 200, 225, 250, 400, and 500, the last being the line pressure. If it is desired to go still further and add some small complication, the small motors may be used part of the time as boosters; that is, they could be reversed and driven by the other motors as generators for raising the pressure applied to the large motors. This method would add to the other equivalent speeds, the pressures of approximately of 280, 320, and 640. The whole range of speed could thus be covered by pressure control. The use of the small motors as boosters is mentioned merely to show the possibilities of the case but is not recommended for ordinary service.

Now, the question arises as to what is to be gained by this method of control and what equipment would be recommended. Take, for example, the case of a car ordinarily requiring an equipment of four 50-h.p. motors. In place of that equipment there would be two 75-h.p. and two 25-h.p. motors, the former being standard railway motors and the latter being standard type but wound for 125 volts. The advantages gained would be in accelerating with about 20 per cent. less current, in reducing the peaks on power-house load, in having five efficient speeds instead of two, and in substituting two 125-volt motors for two 500-volt motors which would decrease the cost of maintenance.

Another example would be found in the elevated railways where two-motor equipments are used. It would pay to add two small motors to each motor-car to reduce the load on the power-house or to increase the rate of acceleration or loads carried.

The disadvantages are few. It means two sizes of motors instead of one; but, as stated above, the small motors are wound for low pressure and will have a very low cost of maintenance, as the windings will in all cases be of comparatively heavy copper which is susceptible of the highest insulation. The commutators will take care of themselves.

Another disadvantage might be that if the wheels driven by the small motor should slip, the motor might have several times its normal pressure applied to it and would be injured thereby. Such a contingency is extremely remote, however, because the wheels have nearly as much weight on them as those driven by the large motors and only one-fourth of the torque applied to them.

One more objection is that the car is carrying motors around that are used only a part of the time. This is true, but they are used practically all the time except when the car is running with light loads; and the capacities of the motors can be arranged so that there will be no excess capacity carried.

Before leaving the question of speed regulation, it is well to

point out the fact that the foregoing applies only to direct-current motors and is entirely unnecessary with the single-phase motors where any pressure within the capacity of the motor may be easily and efficiently applied to it by means of the induction regulator or by the auto-transformer with a number of loops brought out. This system thus possesses the advantage which it is impossible to attain entirely with the direct-current system.

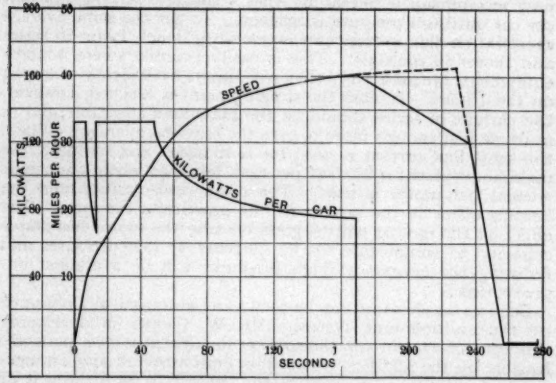


FIG. 2.

Total weight of car loaded—tons	39.5
Length of run—miles	2.2
Schedule speed—miles per hr	28.6
Length of stop—seconds	20
Acceleration—miles per hr. per sec	1.3
Braking rate—miles per hr. per sec	1.5
EQUIPMENT.	
Motors	4–75h.p.
Sq. root mean sq, amperes per motor	41
Sq. root mean sq. kilowatts per car	79
Average kilowatts per car	60.5
Pressure at car	550

Besides the lack of efficient speed regulation, the interurban railways are great sufferers from the tremendous fluctuations of load on their power stations and sub-stations. Since most of such roads operate with a small number of cars, frequently only one on a sub-station at one time, the capacity of the station is fixed entirely by the *maximum* load on it and not at all by the average load. It is thus of the greatest importance to limit the fluctuations of load to the minimum allowable to meet

the conditions of schedule. With the ordinary hand-control it is impossible to keep down the fluctuations except by putting resistance in the line, which is not particularly efficient. Automatic acceleration is therefore desirable, which will take the matter out of the hands of the motorman.

In most places the acceleration is made at a constant rate until full pressure is reached. This means that the same average current per motor is used in series and in multiple, which gives twice as much current per car in multiple as in series. We now recommend accelerating with a constant average current *per car* until full pressure is reached. To get the same average acceleration this necessitates accelerating much faster in series and slower in multiple. This is easily possible where 4-motor equipments are used, since they will always have plenty of weight on the drivers. In case the slipping point is reached, however, the current in series should be the maximum allowable, and in multiple just enough more to give the required average. Where the same line current is used for both series and multiple, the maximum current is 20 to 25 per cent. less than where a constant current per motor is used. The power consumption and the heating effect on the motors will be practically the same. The effect on the motors will be good because the motor has ample capacity to commutate heavy currents at low pressures, and reducing the current at high pressures will be a distinct improvement.

Such an acceleration can be easily and automatically obtained by the multiple-unit system. Mr. W. Cooper in developing this control system for the speaker found that it was perfectly feasible by the addition of suitable limit-switches and arrangement of resistances, to control the current so as to keep it at any desired amount in series and at any amount in multiple.

The use of a different line current in series from that in multiple renders the scheme applicable to any class of service with good results, though of course its advantages are greatest in interurban service where a reduction of 25 per cent. in the maximum current required per car means not only a reduction of the same amount in capacity of the sub-station but a substantial decrease in the amount of copper in the line.

A similar scheme may be applied to the single phase where the insertion of a single limit-switch in the trolley circuit will keep a constant apparent kilowatt on the line and a variable rate of acceleration having its maximum at the start and gradually diminishing until full pressure is reached.

Figs. 1 and 2 show respectively the standard method of accelerating with a constant current per motor and the proposed method for accelerating with a constant current per car. It will be noted that the schedule speed is the same in both cases. The average power consumption and the equivalent heating current per motor are practically the same, while the acceleration in the first case is at the rate of 0.7 miles per hr. per sec. at the maxi-

mum, and in the second case is 1.3 miles per hr. per sec. The important point is that the maximum kilowatt in the one case is 176 while in the second case it is only 132, a reduction of just 25 per cent.

It is probable that the before-mentioned system of speed regulation combined with this scheme of acceleration will give the best operation of which the direct-current system is capable, It will give the greatest economy in power consumption, station capacity, and line copper, and with practically no additional complication or expense.

BLANK
PAGE

A paper presented at the 192d Meeting of the American Institute of Electrical Engineers New York, Dec. 23, 1904.

Copyright, 1904, by A. I. E. E.

THE MAXIMUM DISTANCE TO WHICH POWER CAN BE ECONOMICALLY TRANSMITTED.

BY RALPH D. MERSHON.

As transmission voltages, actual or proposed, become higher and higher and transmission distances reach out farther and farther, it is interesting and profitable to inquire into the probable maximum distance to which power will be commercially transmitted. As with most engineering enterprises, the limitations will come through economic conditions, and the greatest distance to which power will ever be commercially transmitted is the greatest distance to which it can ever be economically (using the word in its broad sense) transmitted.

In endeavoring to make such a forecast, as will be here attempted, it should be borne in mind that each additional limitation consequent upon the assumptions necessary in order to obtain definite representative figures adds to the chance of the forecast proving erroneous. For instance, the first asumption which must be made is that in the future power will be transmitted in the same way as now. This may not hold. There may be devised some other and better way not involving the use of transmission lines. Such, however, does not appear probable. Other assumptions as to methods of construction being the same as, or similar to, those at present in use may be eventually so modified by skill and experience as to change very materially any conclusions arrived at now. This is less improbable. Conditions, industrial and financial, may so change that the constants now assumed as fixing costs, interest, etc., will be materially modified. This is probable. Finally, it is certain that with the course of

time the value of power will increase, and this will materially alter any figures at which we may now arrive. The present conditions of practice and possibility are sufficiently definite, however, to warrant a forecast with the expectation that it will be applicable, approximately at least, for some considerable time to come. At any rate, the mode of treatment of the subject herein adopted will apply so long as present methods of power transmission obtain, and, with suitable changes in the values of the constants involved, afford at any time a means of obtaining a comprehensive view of the possibilites of long-distance transmission.

The elements which, in the broadest sense, limit the distance to which power can be economically transmitted, are two; the cost of power at the generating station, and the price which can be obtained for the delivered power. The difference between these two elements must cover the cost of transmission, the interest on the investment, and the profit. The cost of transmission comprises the loss of power n transmission, the cost of operating, and the cost of maintenance and repair. The value of the sum total of the interest which must be paid upon the investment, and the minimum profit which is considered satisfactory, will have much weight in determining the limiting distance of transmission. The less this sum is the farther power can be transmitted; a low interest rate and a low rate of dividend will, therefore, be conducive to long transmissions.

Let us consider in a general way the manner in which the investment in a transmission plant and the annual charges and expenses in connection with the plant vary with different outputs, voltages, and distances of transmission. For a given voltage, drop, and distance of transmission, the cost of all the apparatus and equipment, except the line conductors, will increase more slowly than the output of the plant. That is, the greater the output of the plant the less the cost per kilowatt of all the equipment, except the line conductors. This will be true of the operating expenses also. Therefore, since the interest charges and the charges for depreciation and repair are dependent upon the investment, the greater the output of the plant the less will be the quantities going to make up the annual cost per kilowatt of transmitting power, except those depending upon the line conductors. Since the weight of the line conductors, under the conditions assumed, will vary directly as the amount of power transmitted, those elements of the annual cost per kilowatt depending upon the line conductors

will be practically constant for all amounts of power transmitted and cannot be materially reduced by increasing the amount of power transmitted. With the same voltage, economic drop, and output, the elements of annual cost per kilowatt due to the line structure (pole line) and to its extent (patrolling, etc.), will increase directly as the distance. But, as outlined above, any increase of cost in line structure due to increase in distance can be offset by increase of output. On the other hand, the weight of the line conductors increases as the distance (for the same *economic* drop) and the elements of annual cost per kilowatt due to the weight of the line conductors will, therefore, increase as the distance, no matter what the output.

It appears, therefore, that all the elements in the annual cost per kilowatt for transmitting power, except those dependent upon the line conductors, may be continually reduced by increasing the amount of power to be transmitted. The annual cost per kilowatt due to the line conductors cannot be so reduced. It can be diminished only by such other means as will reduce the first cost of the conductors. As the first cost of the line conductors can be reduced only by increasing the voltage of transmission and as there is a limit to which such increase can be carried, it follows that *the limiting distance to which power can be economically transmitted will depend, finally, upon the cost of the line conductors and upon this alone.*

The limit of voltage referred to is not necessarily that due to physical considerations, such as difficulties of construction, air losses between conductors, etc.; for, leaving such matters out of consideration, it is easy to imagine the voltage carried to such a high value as will reduce the line conductors to the point where the increased cost of transformers and insulators, due to a further increase of voltage, will overbalance the saving in the line conductors, due to such further increase.

It will somewhat simplify the treatment of the subject if the interest charge be included as a part of the cost of transmission, and profits be represented by a percentage on the investment. This course will, therefore, be pursued. That is, it will be assumed that in the cost of transmission is included the interest on the investment (bond interest) and that over and above this cost there must be earned a certain percentage, which percentage will represent profits (stock dividends). In addition the following assumptions will be made:

Power purchased at low-tension bus-bars of step-up transformers and sold at outgoing bus-bars of the step-down station.

Frequency of transmission not less than 25 cycles nor more than 30 cycles as being the limiting frequencies which, while favorable to the transmission of power, are yet suitable for almost all purposes to which power can be applied.

Idle synchronous motors at step-down station to correct for power-factor, the average power-factor of the line being held as near unity as possible. In the plants of large output dealt with below, the possible approximation to unity power-factor will, in spite of the line-charging current, be sufficiently close, for practical purposes, to justify the assumption of unity power-factor.

That no matter what the capacity of the plant, there will be three transmission circuits, each upon its own pole line, and each capable of carrying one third the load.

That the power-factor of the load supplied will be 0.8.

That no matter what the size of the plant the number of transforming units at each end of the line be 18, each transformer being normally worked at $\frac{1}{6}$ of its rated capacity, so that one bank of three may be cut out, if need be.

That no matter what the size of the plant the number of corrective synchronous motors will be six, each being worked at $\frac{1}{4}$ of its rated capacity. The kilovolt-ampere capacity of these synchronous motors must, for a load power-factor of 0.8, be equal to $\frac{3}{4}$ of the kilowatt capacity of the load carried by the plant.

It is evident that the number of units must be considered as the same for plants of all capacities in order to take full advantage of the decrease of cost per kilowatt, due to increase of capacity.

The pole lines will be assumed as constructed with 12 steel towers to the mile.

Ideal conditions will be assumed throughout consistent with delivering reliable and cheap power. Since the object is to determine the *maximum* distance, the factors fixing commercial costs of apparatus will be taken at the lowest values likely to obtain.

Later on in this paper general equations are derived expressing the relations between the distance of transmission and the quantities which govern it. By making assumptions, in addition to those mentioned above, as to the values of the

various coefficients in the general equations and as to the purchase price and selling price of power, the curves of Figs. 1, 2, 3, 4, 5, and 6 have been obtained which are given and discussed here instead of at the end of the paper.

Fig. 1 shows the relation between the distances of tranmission, D, and the economical voltage, E, for different kilowatt outputs, W; that is, it shows the voltage which it is most economical to use

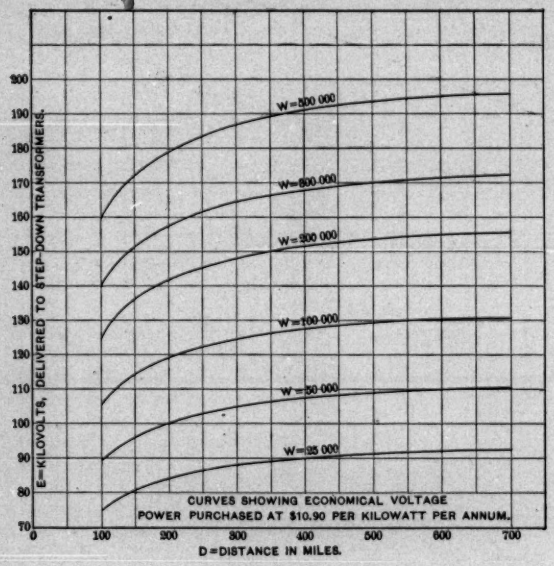


FIG. 1.

for any given output and distance of transmission.

Fig. 2 shows, in a corresponding manner, the economical drop.

Fig. 3 shows the diameter of the conductors corresponding to the conditions of Figs. 1 and 2.

Fig. 4 shows the relation between D, the distance of transmission, and p, the percentage net profit on the investment for

different values of output W and for selling price of $34 per kilowatt per annum.

Fig. 5 is similar to Fig. 4 but applies to a selling price of $20 per kilowatt per annum.

Fig. 6 shows for different selling prices the relation between

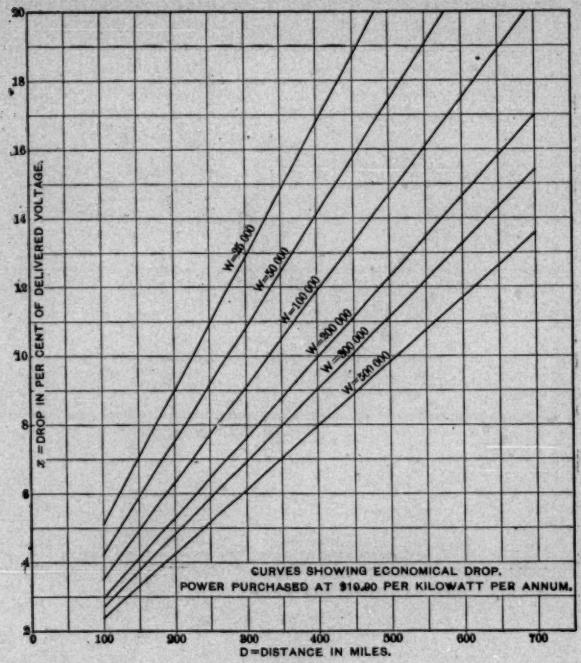


FIG. 2

the distance of transmission and the output for a net profit of 12%. The lower curve of Fig. 6 is derived from Fig. 4 by plotting the distances and outputs of Fig. 4 corresponding to a net profit of 12%. In a similar manner the upper curve of Fig. 6 is obtained from Fig. 5. The other curves of Fig. 6 were ob-

tained from other sets of curves (not included herein), similar to those of Fig. 4 and Fig. 5, and applying to the other prices of power to which Fig. 6 applies.

In obtaining these curves the constants have all been given

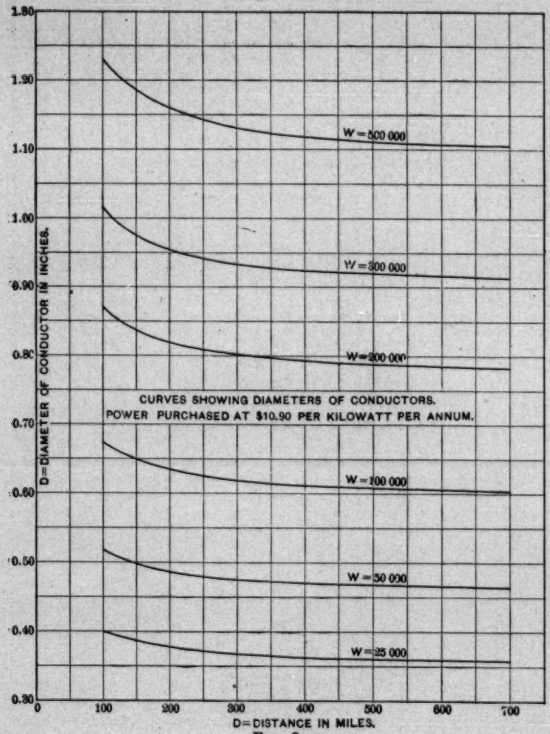


FIG. 3.

values favorable to long transmission distances. The costs have been taken lower than those ordinarily current in the endeavor to anticipate somewhat possible future prices. Also, the cost of power purchased at the step-up station has been fixed

at the very low figure of $10.90 per kilowatt per annum. These facts should be carefully borne in mind in considering the curves, which will all be more or less modified by changes in the quantities mentioned.

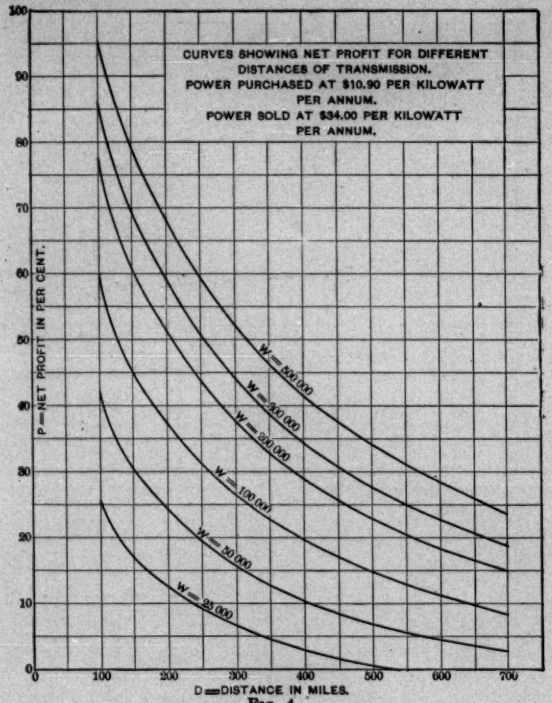


FIG. 4.

On comparing the diameters of conductors given by Fig. 3 and the voltages to which they correspond with the values of diameter and critical voltage given by Professor Harris J. Ryan in his splendid paper on that subject,* it appears that the diameters of Fig. 3 are considerably above those of the paper men-

*See paper read by Professor Ryan before AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS, February 26, 1904.

tioned. The values of Fig. 3 are affected by the price paid for power at the step-up transformers, but if this be taken even as high as $20 per kilowatt per annum instead of $10.90, the diameters of the conductors remain below those for the critical voltages. It appears, therefore, in the light of present knowledge, that the limit of voltage will come through economic conditions and not through conditions depending upon atmospheric losses.

It is difficult to fix upon a figure for the selling price of the delivered power which shall be representative. Power prices are so dependent upon conditions, especially those arising from the location and magnitude of the market and of the supply, that any figure chosen will be objected to by some as too high and

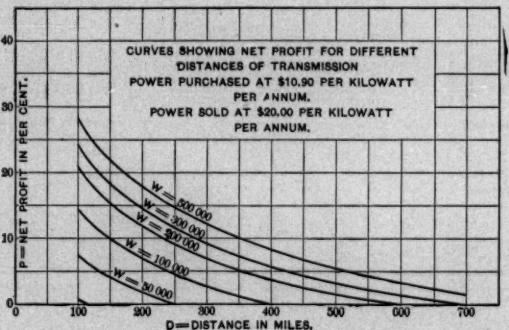


FIG. 5.

by others as too low. The same statement applies to the price assumed as that paid for power at the step-up station, but in a lesser degree. The selling prices of $34 and $20 have been chosen as the upper and lower limits for the price of power in such large amounts as are under consideration.* While it is unquestionably true that in some parts of the country power is worth, and will bring, much more than $34, the markets where such prices are obtainable are not very large; in the East, where large markets are possible, much more than $34 cannot be expected for very large amounts of power.

* The paper as originally presented contained curves applying to the selling price of $34.00 only.

On the other hand, $20 is believed to be as low as will obtain under any other than the most exceptionable circumstances. Fig. 6 covers this range of prices, giving curves for intermediate prices as well as the limiting prices mentioned.

The voltages to which the curves apply are much higher than those now in use commercially, but they are not beyond the range of future possibility. Manufacturers will now undertake commercial transformers for voltages as high as 150 000

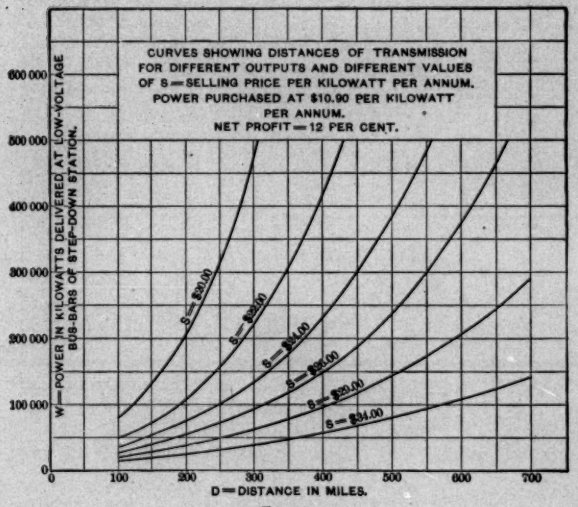


FIG. 6.

volts, and there is little question that when the demand shall come for units of the large capacities contemplated herein, the voltage requirements will be met. Such transformers will be structures of sufficient size to permit of being gotten at and worked upon from the inside as well as the outside and this, in connection with the fact that more space may be utilized for insulation, will render construction for high voltages much less difficult than at present.

The maximum amount of power dealt with herein, 500 000 kilowatts, is probably too high to be seriously considered at this time, but from 200 000 to 300 000 kilowatts is believed to be within the range of immediate future possibility. In a plant of this size it is probable that a net profit of 12% would be required, not alone for the purpose of dividends, but also as a protection to the bonds. A price of $26 per kilowatt per annum is probably a fair price to assume for the delivered power in such large quantities as are contemplated. Under these conditions Fig. 5 shows the distance of transmission to vary from 463 miles for 200 000 kilowatts to 552 miles for 300 000 kilowatts. For the present outlook, therefore, the limiting distance may be taken as about 500 miles.

It appears from the preceding matter that under the conditions assumed, the limiting distance of transmission will, for some time at least, be in the neighborhood of 500 miles.

It also appears that voltage limits will be fixed, not by conditions depending upon atmospheric losses, but by economic conditions.

The latter conclusion, while recognized as a possibility when this paper was begun, was unexpected. It is, perhaps, of greater present importance than the original object of the paper as conveyed in the title.

* * * * * * * * * *

The analysis on which depends the general equations from which the preceding curves were obtained will now be taken up.

Let E = voltage, in kilovolts, delivered to step-down transformers.

D = distance of transmission in miles.

x = percentage of power lost in the line in terms of delivered power.

e = efficiency of the whole system.

e_1 = combined efficiency of step-up and step-down transformers and synchronous motors.

d = diameter of line conductors in inches.

W = power, in kilowatts, delivered at low-voltage bus-bars of step-down station.

c = cost, in dollars per kilowatt per annum of power purchased at the low-voltage bus-bars of the step-up transformers.

Let s = price, in dollars, received for power per kilowatt per annum at the low-voltage bus-bars of the step-down station.

h = a quantity which, multiplied by c, will give the cost at the high-voltage terminals of step-up transformers.

R = total interest maintenance and depreciation charge per annum.

L = cost of labor for operating transformer stations and for executive and clerical services.

M = total investment.

C = total cost per annum of power delivered, inclusive of interest.

p = a percentage covering profit.

$\therefore \quad e = \frac{e_1}{1+x}$, since $\frac{1}{1+x}$ is the efficiency of the line.

$\therefore \quad \frac{W c}{e} = \frac{W c\,(1+x)}{e_1}$ = total amount expended per annum for power purchased.

$\therefore \quad W s$ = total amount received per annum for power.

$$\therefore \quad C = \frac{W c}{e} + L + R$$

$$\therefore p = \frac{W s - C}{M} = \frac{W s - \frac{W c}{e} - L - R}{M} = \frac{W s - \frac{W c\,(1+x)}{e_1} - L - R}{M} = \frac{N}{M} \tag{1}$$

Now M is made up of

(1) Cost of transformers.
(2) Cost of transformer switchboard apparatus, cables, lightning protection, etc.
(3) Cost of building and real estate.
(4) Cost of insulators.
(5) Cost of pole-line material and construction.
(6) Cost of right of way.
(7) Cost of corrective synchronous motors and exciters.
(8) Cost of switchboard apparatus, cables, etc., for synchronous motors.
(9) Cost of line conductors.

Cost of transformers will depend upon voltage and output

$f_1(E,W)$

Cost of transformer cables and controlling apparatus will depend upon same quantities as transformers, but in a different way;

$f_2(E,W)$

Cost of building will depend upon output;

$f_3(W)$

Cost of insulators will depend upon voltage, diameter of conductors and number required; *i.e.*, voltage, diameter of conductor, and distance of transmission;

$f_4(E, d, D)$

Cost of pole-line construction will depend upon diameter of the conductors and the distance. But the diameter of the conductors depends upon voltage, drop, output, and distance; hence,

$f_5(d, D) = f_5(E, W, x, D)$

Cost of right of way will depend upon distance only;

$f_6(D)$

Cost of synchronous motors will depend upon output only, since all other elements affecting cost will be fixed;

$f_7(W)$

Cost of switchboards and cables for synchronous motors will depend upon output only;

$f_8(W)$

Cost of line conductors will depend upon voltage, output, line loss allowed, and distance of transmission;

$f_9(E, W, r, D)$

The sum of these nine functions constitutes M, the total investment.

Now R, the total interest and depreciation charge, depends upon all of the several quantities making up M.

In what follows the numerical values of the constants are those taken for the specific problem treated herein.

Let $p_1 = 0.125$, being the percentage of transformer cost for interest, depreciation, and repairs.

$p_2 = 0.125$, being the percentage of transformer switchboards cost for interest, depreciation, and repairs.

$p_3 = 0.075$, being the percentage of buildings cost for interest, depreciation, and repairs.

$p_4 = 0.10$, being the percentage of insulator cost for interest, depreciation, and repairs.

$p_5 = 0.125$, being the percentage of pole line cost for interest, depreciation, and repairs.

$p_6 = 0.05$, being the percentage of cost of right of way, for interest only.

$p_7 = 0.125$, being the percentage of synchronous motor cost of interest, depreciation, and repairs.

$p_8 = 0.125$, being the percentage of cost of synchronous motor,

switchboard, etc., for interest, depreciation, and repairs.

$p_9 = 0.05$, being the percentage of cost of conductors, for interest.

R = the sum of these percentages multiplied respectively into the several quantities to which they refer

L depends upon output only

$$f_{10}(W)$$

The numerical values given for the percentages p_1, p_2, etc., are those which will be used in the specific problem herein treated. The rate of interest has in all cases been taken as 0.05, so that by subtracting this from the above values the depreciation assumed in each case may be determined.

If there be substituted in equation (1) the values of M, L, and R, as expressed by the above symbols, there will result an equation expressing in the most general terms the relations between the distance of transmission and the quantities which govern it. This substitution results in rather an unwieldy expression and will be omitted.

Before proceeding with the determination of the forms of the several functions indicated it will be necessary to enter into a discussion of the relations existing between voltage and line loss, and the quantities governing them respectively.

Let q = that portion of the cost per kilowatt at the low-tension bus-bars of the step-down station, which is due to line loss and to interest on the value of the conductors; then, anticipating in part the matter of a few pages further on

$$q = \frac{p_9 K_9 \frac{W D^2}{E^2 x} + hc\, Wx}{W}$$

in which $p_9 K_9 \frac{W D^2}{E^2 x}$ is the interest on the conductors and $hc\, Wx$ the cost of the power lost in the line.

Setting the first derivative of this with respect to x equal to zero, in order to determine the value of x corresponding to the minimum value of q, we find the well known expression for economic drop

$$x = \left(\frac{p_9 K_9}{hc}\right)^{\frac{1}{2}} \frac{D}{E} = n \frac{D}{E} = 0.038 \frac{D}{E} \qquad (2)$$

From this equation for x we may obtain the equation

$$p_0 K_0 \frac{D^2}{E^2 x} = hcx$$

But the first member of this equation is the interest on the line conductors per kilowatt delivered, and the second member is the annual cost of the line loss per kilowatt delivered. That is, for the most economical conditions the line loss per kilowatt delivered must be equal in value to the interest on the conductors per kilowatt delivered—a relation already well known.

As has already been suggested, there will be a limit to which the voltage can be carried, due to the fact that, although increase of voltage will diminish the annual cost of lost power and of conductors, it will increase the annual cost of certain other important factors. The elements of annual cost which are affected by change of voltage are the interest and depreciation of the transformers, the interest on the line conductors, the line loss, and the interest and depreciation of the insulators. The first and last items will increase with the voltage, because of the increased first cost, due to the increase of voltage; the other two will diminish.

Let q_1 = that portion of the annual cost per kilowatt of delivered power due to the line loss, conductors, insulators, and transformers. It has just been shown that for best economy the line loss and annual conductor cost must be equal, so that twice the line loss, $2\,hc\,Wx$, may be taken as representing the sum of the annual cost due to line loss and to the conductors. As will be shown later, the cost of the insulators will vary as the distance of transmission, and as the cube of the voltage and the cost of the transformers may be represented by

$$K_1'\,(E+K_1'')\,W^{\frac{1}{2}}$$

Hence remembering that p_1 and p_4 are the interest and depreciation of transformers and insulators, respectively,

$$q_1 = \frac{2\,hc\,W\,x + p_4 K_4 E^3 (1+x)^3 D + p_1 K_1'\,(E+K_1'')W^{\frac{1}{2}}}{W}$$

or, putting in the value of $x = \left(\frac{p_0 K_0}{hc}\right)^{\frac{1}{2}} \frac{D}{E} = n\frac{D}{E}$.

$$q_1 = \frac{2\,h\,n\,WDE^{-1} + p_4 K_4 E^3 (1+n\,DE^{-1})^3 D + p_1 K_1'(E+K_1'')W^{\frac{1}{2}}}{W}.$$

Now if the first derivative of q_1 with respect to E be set equal to zero to determine the best value of E, there results a quartic equation more interesting than valuable, so far as the present purpose is concerned. It will greatly simplify matters if instead of substituting the value of x in $(1+x)^3$ we substitute for x, x_1, a fixed drop of such value as will correspond to the average cost of insulator between the two extreme values of x which will be met with in practice; as will be shown later, the error due to such a course will be small. Hence

$$q_1 = \frac{2\,hcn\,W\,D\,E^{-1} + p_4 K_4 E^3 (1+x_1)^3 D + p_1 K_1' (E + K_1'') W^{\frac{1}{2}}}{W}.$$

Setting the first derivative of this equation equal to zero, solving and substituting the value $n = \left(\frac{p_9 K_9}{h\,c}\right)^{\frac{1}{3}}$ there results

$$E = \left(\frac{-p_1 K_1' W^{\frac{1}{2}}}{6 p_4 K_4 (1+x_1)^3 D} + \sqrt{\frac{p_1^2 K_1'^2 W}{36 p_4^2 K_4^2 (1+x_1)^6 D^2} + \frac{2 (hc p_9 K_9)^{\frac{1}{3}} W}{3 p_4 K_4 (1+x_1)^3}}\right)^{\frac{1}{3}}$$

$$= \left(-3066 \frac{W^{\frac{1}{2}}}{D} + \sqrt{9400356 \frac{W}{D^2} + 3438.5\, W}\right)^{\frac{1}{3}} \qquad (3.)$$

This shows that the voltage may be increased with increase of output, which was to be expected since those costs which limit the voltage will diminish in their amount per kilowatt as the output increases. The value of x_1 used in the above equation was determined upon as follows: The minimum percentage drop which is ever likely to obtain is, say, 2.2; the maximum is, say, 11.5. The reason for selecting these values will be apparent on considering the values of E calculated from the above equation, and given below, in connection with the values of W to which they correspond, and the respective distances to which in each case the various amounts of power would probably be transmitted. The intermediate value of drop which will give the average insulator cost is 6.45%, and this value of x_1 is taken. With this value of x_1 the maximum error in insulator cost, between the limits assigned, will have place when $x = 2.2$ and $x = 11.5$. The percentage error at either of these limits is about 13%. But, as appears in the solution of the first derivative, at the point of minimum of the variables affected by the voltage the com-

bined values of the annual cost due to the conductors, the annual cost of the line loss, and that portion of the annual transformer cost due to voltage, is more than three times that due to the insulators. The total variable quantity involved, therefore, is more than four times the annual cost due to insulators, and the error as a percentage of the total of values of the variables involved is less than $\frac{13}{4} = 3.25$, instead of 13%. As will be seen on examining the manner in which x_1 enters the equation for E, the maximum error in E will be less than 3%, also which will to a like extent affect the values of x. This error is negligible so far as the main problem is concerned, and indeed so far as the question of voltage itself is concerned.

In Fig. 1 are shown curves plotted from equation (3). These curves show the kilovolts E for different distances D, and different outputs W. Fig. 2 gives curves plotted from equation (2), using the values obtained from the curves of Fig. 1. The curves of Fig. 2 show the percentage drop x for different distances D, and different outputs W. In Fig. 3 are curves showing the diameters of the conductors for the conditions of Figs. 1 and 2. These diameters were calculated from the formula

$$d = k'_5 \left(\frac{WD}{E^2 x}\right)^{\frac{1}{2}} = k'_5 \left(\frac{WD}{E^2} \frac{E}{nD}\right)^{\frac{1}{2}} = \frac{k'_5}{n^{\frac{1}{2}}} \left(\frac{W}{E}\right)^{\frac{1}{2}} = 0.0219 \left(\frac{W}{E}\right)^{\frac{1}{2}} \quad (4)$$

which gives the diameter d, in inches, of a *solid* conductor. These diameters were in this case calculated for a solid conductor instead of a stranded one because we have at present available data as to the critical point in the atmospheric loss curve for solid conductors only, and while perhaps this critical point will come at a higher voltage in the case of the stranded conductor with its greater diameter, there are no definite data at present on the subject. On comparing the diameters of conductors given by Fig. 3 and the voltages to which they correspond with the values of diameter and critical voltage given by Professor Ryan* we see that the diameters of Fig. 3 are considerably above those of Prof. Ryan's paper. It appears, therefore, from the present knowledge available, that the limit of voltage will come through economic conditions, and not through limitations connected with atmospheric losses.

*See foot note, page 766.

In the determination of both x and E the quantity h has been employed. This quantity is a factor which, when multiplied into the cost of power at the low-tension bus-bars of the step-up transformers, will give the cost of power at the high-tension terminals of the transformers. That is to say, h takes account of all charges which should be made against this power, including interest and depreciation of the step-up station, transformers, etc., and labor for operating the station, also the loss in the transformers. Now, strictly, there should be substituted for h, the proper functions of the quantities on which it depends, but to do so would seriously complicate the equations and would be of little utility, since h can be approximated with sufficient accuracy in any particular case, and the manner in which it occurs in both x and E is such as to make the error in the quantities due to an error in h much smaller than the error in h itself. In the specific problem herein the value $c = 10.9$ is taken as being the lowest which will probably ever obtain, where large amounts of power are available within transmission distance of a desirable market. The value taken for h in the determination of E and x is $h = 1.1$, so that $hc = 12$.

The next step is the determination of the forms of the several functions indicated. In what follows the constants have been evaluated for the specific problem herein. The costs resulting from the use of these constants will be found to be, in general, considerably less than present commercial costs. The constants were purposely based on prices less than can be now obtained, in the endeavor to anticipate, somewhat, possible future prices.

From a careful consideration of transformer prices, it has been determined that, for transformers of 1500 kw. and over, the cost, installed, very closely follows the law,

$$f_1(E, W) = K_1'(E+K_1'')W^{\frac{5}{6}} = 13.(E+K_1'')W^{\frac{5}{6}},$$

$$\therefore p_1 f_1(E, W) = p_1 K_1'(E+K_1'')W^{\frac{5}{6}} = 1.625(E+K_1'')W^{\frac{5}{6}}$$

in which K_1' is a constant and K_1'' a "variable constant," a quantity which varies slowly with the output in accordance with the law,

$$K_1'' = k_1 + k_1'' W = 55 + 0.000227 W$$

Theoretically the transformer cost would vary with the drop x_1, since the step-up transformers would have an output and voltage greater than the step-down transformers. Prac-

tically, however, step-up and step-down transformers are built so nearly in the same lines that the drop would make little difference. Such difference as would exist can be taken care of approximately by adjustment of the constants, which has been done.

While the apparatus for the control of the high-tension side of the transformers would theoretically vary with the voltage, such variation for 50 000 volts and over will be small, since in most modern plants the high-tension switching apparatus is simple; and higher voltages are likely to cause it to remain so. The lightning protection for the high-voltage lines might vary with the voltage, but it is probable that for high voltages there will soon be a reversion to much simpler and inexpensive apparatus than we use now, so that the variation, if any, due to higher voltages, will be negligible. The switchboard for the lower voltage side of the transformers will vary only with the output, since we assume the lower voltage to be the same in all cases, say 6000 volts or thereabouts. The apparatus for the control of transformers may, therefore, be considered as depending only upon output. Under this assumption a consideration of costs of transformer controlling apparatus and cables, shows that we may assume, with a close degree of accuracy, that

$$f_2(E, W) = K_2' + K_2'' W = 21\,000 + 0.9\ W$$

$$\therefore p_2 f_2(E, W) = p_2 K_2' + p_2 K_2'' W = 2625 + 0.1125\ W$$

The cost of buildings and the real estate for them will increase very slowly with the output. The variation of this item due to variation of output can be expressed closely enough by

$$f_3(W) = K_3' + K_3'' W^{\frac{1}{2}} = 125\,000 + 125\ W^{\frac{1}{2}}$$

$$\therefore p_3 f_3(W) = p_3 K_3' + p_3 K_3'' W^{\frac{1}{2}} = 9375 + 9.375\ W^{\frac{1}{2}}$$

The cost of an insulator will, theoretically, vary with the diameter of the conductor and the voltage. Practically, however, the diameter of the conductor will have nothing to do with the cost. A consideration of insulator prices shows that the cost of an insulator will vary as the sum of a small constant plus the product of a constant into the cube of the voltage. With high voltages the small constant is negligible, so that we may write

$$f_4(E, d, D) = K_4 E^3 (1+x_1)^3 D = 0.000732\ (1.0645)^3 E^3 D = 0.000883\ E^3 D.$$

$$\therefore p_4 f_4(E, d, D) = p_4 K_4 E^3 (1+x_1)^3 D = 0.0000883\ E^3 D$$

The cost of the pole-line material and construction will depend somewhat upon the diameter of the conductors, since, as the diameter of the conductors increases, the wind and sleet stresses will increase. The increase of cost with increase in diameter of conductors will be slow. The law followed will be that of a constant plus a function of the diameter of conductors, since, no matter how small the diameter of conductor, there will be a certain cost representing the minimum sized pole which would be employed. We may, with a fair degree of accuracy, write

$$f_5(d, D) = (K_5' + K_5'' d)\, D = f_5(E, W, x, D)$$

$$= K_5' D + K_5'' k_5 \left(\frac{W D}{E^2 x}\right)^{\frac{1}{2}} D$$

or, putting in the value of $x = n\frac{D}{E}$,

$$f_5(E, W, x, D) = K_5' D + \frac{K_5'' k_5}{n^{\frac{1}{2}}} \left(\frac{W}{E}\right)^{\frac{1}{2}} D = 3000\, D + 37.2 \left(\frac{W}{E}\right)^{\frac{1}{2}} L$$

$$\therefore p_5 f_5(E, W, x, D) = p_5 K_5' D + p_5 \frac{K_5'' k_5}{n^{\frac{1}{2}}} \left(\frac{W}{E}\right)^{\frac{1}{2}} D$$

$$= 375\, D + 4.65 \left(\frac{W}{E}\right)^{\frac{1}{2}} D$$

which answers for a stranded conductor.

Cost of right of way will be directly proportional to distance, hence

$$f_6(D) = K_6 D = 1000\, D$$

$$\therefore p_6 f_6(D) = p_6 K_6 D = 50\, D$$

A consideration of synchronous motor prices shows that the cost of synchronous motors may be written,

$$f_7(W) = K_7' + K_7'' W = 12\,000 + 5.4\, W$$

$$\therefore p_7 f_7(W) = p_7 K_7' + p_7 K_7'' W = 1500 + 0.675\, W$$

The switchboards and cables for the motors will follow the same law as those for the transformers, hence

$$f_8(W) = K_8' + K_8'' W = 8400 + 0.17\, W$$

$$\therefore p_8 f_8(W) = p_8 K_8' + p_8 K_8'' W = 1050 + 0.02125\, W$$

From the well known relations between the cost of con-

ductors, and the voltage, distance, output, and drop, we may write

$$f_9(E, W, x, D) = K_9 \frac{W D^2}{E^2 x} = 0.346 \frac{W D^2}{E^2 x}$$

or, putting in the value of $x = n \frac{D}{E}$

$$f_9(E, W, x, D) = K_9 \frac{W D}{E n} = \frac{K_9}{n} \frac{W D}{E} = 9.1 \frac{W D}{E}$$

$$\therefore p_9 f_9(E, W, x, D) = p_9 K_9 \frac{W D}{E n} = 0.455 \frac{W D}{E}$$

The cost of labor, for the operation of the step-up and step-down transformer stations, and for executive and clerical purposes, would probably not vary at all. We have, in each case, the same number of units to be looked after, and the size of these units would make little, if any, difference in the cost of attendance upon them. Similarly, the output will make little difference in executive and clerical costs. We should probably be justified in making $f_{10}(W)$ a constant. In order, however, to cover such small increase in labor and salaries as there might be with increase of output we will write

$$f_{10}(W) = K_{10}' + K_{10}'' W^{\frac{1}{2}} = 32\,000 + 26 W^{\frac{1}{2}}$$

It is to be noted that the labor in connection with the line is taken care of in the depreciation and repair percentages applicable to the supporting structure and insulators respectively.

The efficiency of the whole system is $\frac{e_1}{1+x}$

Putting in the value of $x = n \frac{D}{E}$

$$e = \frac{e_1}{1 + n \frac{D}{E}} = \frac{0.925}{1 + 0.038 \frac{D}{E}}$$

$$\frac{W c}{e} = \frac{W \left(1 + n \frac{D}{E}\right) c}{e_1} = \frac{W c}{e_1} + \frac{n c}{e_1} \cdot \frac{W D}{E} = 11.78 W + 0.448 \frac{W D}{E}$$

The various functions above arrived at may now be utilized in obtaining N and M of equation (1), $p = \frac{N}{M}$.

Remembering that R is the sum of the products of the various functions by the corresponding percentages representing interest, depreciation, and repair; that $L = f_{10}(W)$, and representing the various resulting collections of constants as follows

$$
\begin{aligned}
a &= p_2 K_2'' + p_7 K_7'' + p_8 K_8'' &&= 0.788 \\
b &= K_{10}' + p_2 K_2' + p_3 K_3' + p_7 K_7' + p_8 K_8' &&= 46\,550 \\
m &= K_{10}'' + p_3 K_3'' &&= 35.38 \\
r &= p_5 K_5' + p_6 K_6 &&= 425
\end{aligned}
$$

$$
\text{then } N = W s - \frac{W c\,(1+x)}{e_1} - L - R
$$

$$
= (s - \frac{c}{e_1} - a)\, W - \left(\frac{nc}{e_1} + \frac{p_9 K_9}{n}\right) \frac{W D}{E} - m W^{\frac{1}{2}} - p_1 K_1' (E + K_1'') W^{\frac{1}{2}}
$$

$$
- p_4 K_4 (1+x_1)^3 E^3 D - r D - \frac{p_5 K_5'' k_5}{n^{\frac{1}{2}}} \left(\frac{W}{E}\right)^{\frac{1}{2}} D - b.
$$

Representing constants as follows

$$
\begin{aligned}
\alpha &= K_2'' + K_7'' + K_8'' &&= 6.47 \\
\beta &= K_2' + K_3' + K_7' + K_8' &&= 166\,400 \\
\gamma &= K_5' + K_6 &&= 4000
\end{aligned}
$$

$$
M = \alpha W + \frac{K_9 W D}{n E} + K_3'' W^{\frac{1}{2}} + K_1' (E + K_1'') W^{\frac{1}{2}}
$$

$$
+ K_4 (1+x_1)^3 E^3 D + \gamma D + \frac{K_5'' k_5}{n^{\frac{1}{2}}} \left(\frac{W}{E}\right)^{\frac{1}{2}} D + \beta.
$$

These values of N and M, if substituted in equation (1) will give, in its final form, the equation connecting distance, output, voltage, and profit, or, in connection with equation (3), for voltage, the relation between distance, output, and profit. Such substitution results in a cumbersome equation and will not be made here. If the various numerical values, already determined for the specific problem herein treated, be substituted in N and M, there results,

$$
N = (s - 12.57)\, W - 0.903 \frac{W D}{E} - 35.38\, W^{\frac{1}{2}} - 1.625\, (E + K_1'') W^{\frac{1}{2}}
$$

$$
- 0.0000883\, E^3 D - 425\, D - 4.65 \left(\frac{W}{E}\right)^{\frac{1}{2}} D - 46\,550
$$

$$
M = 6.47\, W + 9.1 \frac{W D}{E} + 125 W^{\frac{1}{2}} + 13 (E + K_1'') W^{\frac{1}{2}} + 0.000883 E^3 D
$$

$$
+ 4000\, D + 37.2 \left(\frac{W}{E}\right)^{\frac{1}{2}} D + 166\,400.
$$

Putting in this equation the various values of s and calculating the value of p for different outputs, W, and different distances D, the curves of Fig. 4 and Fig. 5 (and the other sets of similar curves for other prices of power) have been obtained. These curves show, for different values of W, the relation between p and D. Assuming that the minimum acceptable profit is 12 per cent. and taking from Fig. 4 and Fig. 5 and the other sets of similar curves (not included herein) the values of D and W corresponding to this percentage profit, there has been plotted the final curve, Fig. 6, which shows the relation between distance and output for the percentage profit assumed.

In considering these curves, the assumption made in connection with them should be carefully borne in mind. A small change in the purchase price or selling price of power will make a great difference in the result. Smaller amounts of power will in general be purchased at a higher price per kilowatt, but on the other hand they would probably be transmitted to points where the power would bring a higher price, since in general, the larger the market the cheaper can power be produced by steam; this fact compensates somewhat for the error in assuming the same purchase price for large and small amounts of power.

It would be interesting to let $s - c'e_1$ equal to zero and determine p which would then be the cost, including interest, of operating the plant. If curves showing the percentage of the investment for operation were thus determined, also the total cost of the plant, both for various outputs, the results would be valuable in preliminary estimates. The writer hopes to work up such data, later.

It will be noticed on referring to the curves that some of them reach to distances which cause the drop to exceed the value taken for the upper limit of drop in connection with insulator cost. The error due to 1 or 2% excess will not greatly affect the final result. It would have been somewhat better however to have chosen the limits of drop as 5% and 15% respectively instead of those taken.

Discussion on "The Maximum Distance to Which Power Can be Economically Transmitted."

President Lieb: It is gratifying to have had another pioneer paper from Mr. Mershon, presenting data for the solution of problems in the transmission of electrical energy, an important branch of electrical industry. Large parts of our western territory are vitally interested in the solution of these problems of transmission, notably the Pacific coast territory and vast tracts of land in need of irrigation.

The bringing of cheap industrial power into the mining centres is doing much toward lessening the cost of handling ores, making it possible to develop the poorer grades of ore. In the South also the economic conditions have been vastly improved by the utilization of the natural sources of power.

In Switzerland and Italy, for instance, it is hardly too much to say that the future prosperity of those countries is intimately bound up with the utilization of the vast sources of natural power, the "white coal" of the Alps.

While the speaker has no data at hand as to the extent to which the coal consumption is affected by the utilization of the water courses, the effect must be important, as industrial centres like the plain of Lombardy (Italy) are no longer operating their cotton mills and silk mills by steam power, but are now dependent upon electric power from transmission plants. When it is considered that almost all of the coal consumed in Italy is brought in bottoms from England, it is evident what an economic evolution such a change represents.

H. G. Stott: This paper is a most interesting one, not only to the engineer, but to the capitalist; for the modern trend of events shows that at no distant time the steam railroads in this country will in all probability be operated electrically. That in itself brings up the question of the maximum distance to which power can be economically transmitted; and the suggestion occurs at once whether we can transmit our power any more cheaply over wires than we can in the shape of coal in cars, and also which is the more reliable way of doing it. After all, every transmission scheme gets down to the question of reliability. An electrical transmission line, as we well know, is a sensitive piece of apparatus, subject to atmospheric disturbance, subject to the small boy with the kite, and with the piece of wire which he can throw over the line at any time. The freight-car is a pretty hardy piece of apparatus and not only hardy, but it has the possibility of a storage of power in the shape of coal at the point where the power is to be generated. The question of reliability is difficult to define, as to just what we want in the shape of reliability; power would not be considered reliable if the total interruptions per year exceed one hour. That criterion in some cases may be too exacting and in other cases not exacting enough. In large lighting plants, such as there are in New York, an interruption of one hour, unless taken care

of by storage-batteries, would be so serious a menace to the interests of the company and so annoying to the public that it would not be considered for a moment as permissible.

This paper deals with figures of 200 000 or 300 000 kw., and with distances of 550 miles. The transmission of power from Niagara Falls to New York would come well within the limits defined by the author, as the distance is approximately 450 miles and the amount of power used by the large plants in this city approximates 175 000 kilowatts.

The author makes the recommendation: "Frequency of transmission not less than 25 cycles nor more than 30 cycles as being the limiting frequencies," and in the paragraph immediately following is the statement: "Idle synchronous motors at step-down station to correct for power-factor, the average power-factor of the line being held as near unity as possible." By increasing the frequency we increase the capacity current of the line, and in that way can compensate for quite a large lagging power-factor. If there were not so many established plants using 25 cycles, the speaker thinks it would be profitable to discuss the question of using this frequency, whether 25 cycles is not too low. In the west, where 60 cycles is used almost exclusively, the power-factor is nearly always leading. That has another bearing on the cost of copper, and also eliminates the idle synchronous motors, which may be a source of much trouble in the case of disturbances, such as short circuits, on the line.

The principal criticism to be made is that the cost has been worked out without consideration of the load-factor, when it can not be expected that the load-factor will be greater than 50%, and this in turn affects the entire copper calculations. Examination of the mathematical analysis upon which the curves in this paper are based shows that load-factor has been entirely ignored and that the assumption has been made that power can be sold at a uniform price per kilowatt independent of the load-factor. Many attempts have been made to sell power upon this basis, but the speaker's experience is that they have ended in a mutual recognition by the producer and the consumer that it was not fair to the latter. $34.00 per kilowatt would mean that the cost per kilowatt-hour (on one-hour peak load lasting 309 days per annum) would be over 11 cents, or more than double the cost of steam power under the same load-factor. As a general proposition, it may be safely stated that no distant water power transmission plant can compete with a steam plant located near the point at which power is to be delivered, if the load-factor is less than 40% and coal less than $3.25 per ton.

In regard to the figure given of $10.90 per annum per kilowatt for power at the source of supply, there are few if any water-power plants developed for less than $100 per kilowatt, and some have gone as high as $190 per kilowatt, so that if we allow 12.5% for interest, depreciation, etc., as in the author's paper, the minimum cost per kilowatt would vary from $12.50 to $23.75.

PHILIP TORCHIO: Mr. Stott said he looked at this paper from the point of view of transmitting power from Niagara Falls to New York, or to similar large centres where there is a great market for power. This discussion will be somewhat from the same point of view, and not from the point of view of territories, such as exist in the West, where the cost of coal may be a great factor in the development of long-distance power transmission.

The general problem treated by the author involves the study of the two main factors which enter into the problem of power transmission, *i.e.*, the transmission pressure and the cross-section of the conductors. The elements which are affected by the pressure are the cost of transformers and insulators, which increase with the pressure, and the cost of line conductors and line losses, which decrease with the pressure. All the other elements are practically not influenced by the change in pressure. The author has treated the subject in detail, and has given a formula for the determination of the most economical transmission pressure. In this formula there enters the cost of line losses and interest and depreciation on conductors, both of which are dependent upon the most economical cross-section of conductors; therefore the dominating factor in a study of this character is the determination of the cross-section of conductors for the fixed conditions of each problem.

The author has adopted the Kelvin law for the determination of the cross-section of conductors, and he has obtained the results shown in Fig. 3, giving: "The diameter of the conductors for power purchased at $10.90 per kilowatt per annum."

The speaker has, during the last ten years, done considerable work on problems of transmission of power for a great variety of conditions; in all these studies he has made frequent use of the Kelvin law, which has been of great service to him. Its importance, however, is not generally recognized among engineers, perhaps for the reason of the great care which must be used in the selection of the factors entering into the formula, and also on account of the mistaken interpretation of the meaning of the formula which is often expected to give a general solution of any specific problem without regard to other requirements not taken into consideration by the Kelvin law. This law gives with accuracy the most economical cross-section of the conductors of a circuit in which we want a certain current to circulate. Other requirements, such as the safe carrying capacity of wires, the regulation, the brush discharges of high-pressure lines, etc., may substantially modify the conclusions arrived at from the consideration of the theoretical conditions of efficiency alone, and these modifying influences must be given due weight.

The speaker wishes to make a criticism in connection with the author's assumption of $10.90 per kilowatt per annum for the line losses, this being the same amount as paid for the main

bulk of current. The author, in this instance, failed to apply the very same principle which is one of the prominent features of the treatment of his paper, *i.e.*, "That the greater the output of a plant, the less is the cost per kilowatt of all the equipment." Now if there is a case where this general principle is unquestionably correct, it is the case of the increment cost of station equipment for amounts not exceeding say 5% or 10% of the total equipment; that is, if a plant of 100 000 kw. will cost, say $10 000 000 or $100 per kilowatt, we must certainly be able to increase the capacity of the apparatus say 10% at an increment cost considerably less than the average of $100 per kilowatt. The fact that in the paper the power is assumed to be purchased at a fixed rate per kilowatt will not alter conditions, as the saving derived from this increment cost of generating equipment will be felt either directly or indirectly by the transmitting company, either by lower fixed charges for the operation of the generating plant, or lower price of power charged by the generating company. If the transmitting company owns and operates the generating plant as well, nobody will question the above reasoning. The speaker does not see any reason why the same should not hold for the two enterprises operated independently; at least in this theoretical discussion such assumption should be made. If this had been done, perhaps the increment cost of power for line losses and other losses would have been $5.45 instead of $10.90 per kilowatt, while the cost of power delivered would have been slightly increased by the necessary amount so that the average of all power would still amount to $10.90 per kilowatt as before. This change in cost of power for line losses would have considerably changed the final results. The cross-sections of conductors given in Table 3, all of which are based on approximately 2500 circular mils per ampere, would have been changed to the basis of 1750 circular mils per ampere, thereby reducing the total cost of conductors about 30%. The economical voltages of Fig. 1 would have been somewhat changed, while the curves of economical energy drop of Fig. 2 would have been raised about 42%. By referring to Fig. 2 we see that such increase in energy drop would be permissible for all cases up to about 200 miles; this at least for the curves of larger outputs. For longer distances we should meet serious objections, especially for the curves of smaller outputs. These limitations are dependent upon the character of apparatus supplied at the receiving end of the line. In general the presence of different types of apparatus will limit the maximum energy drop to the following amounts:

Synchronous converters, about.....10%
Synchronous motors, about.....15%
Induction motors, about.....20%

This brings into play a new factor which is not taken into account by the formulas. Any conclusions that might be derived from the analytical treatment must be ultimately revised

to meet the above requirements of maximum energy drop. In the case of very long transmission lines, necessarily involving large amounts of power, synchronous converters will usually be found present under existing American conditions. This fact not only would prevent us from reducing the cross-section of conductors as given in the author's paper, but it would also necessitate a further increase of cross-section for reducing the maximum energy drop, and therefore cause a reduction in the limiting distance of the present outlook for power transmission as given in the concluding paragraphs of the paper, where the limiting distance is given as approximately 550 miles.

In making further criticism, the speaker has in mind that this paper is of a pioneer character, and therefore should only be discussed upon broad lines. We must assume ideal conditions and we must even allow something that may appear problematical at the present time. The author has correlated a great amount of knowledge and information in the ten formulas giving the elements of cost of the transmitting systems. The speaker would like to question some of the items and assumptions, for instance; the use of a single pole line and single route; the arrangement and number of transformers for the different outputs; the 5% rate of interest for capital invested in an enterprise of this character; and other items. But he believes it would not be fair nor profitable to open a discussion upon these points. He believes, however, that exception could be taken to some of the fundamental assumptions.

On page 760, first line, the author says; "It is certain that with the course of time the value of power will increase." If this statement is applied to a definite period of time covering say 25 or even 50 years from now, we are entitled to question its plausibility. The cost of power derived from coal will, for centuries to come, apparently govern the cost of power throughout the greater part of the North American continent. If other sources of power be used, they must compete favorably with the power from coal. The coal deposits of the United States and Canada are so large that coal-trade experts have not yet made an inventory of the probable supply. There are now immense coal fields entirely untouched. At present the rate of consumption of coal in the United States is exactly 1 000 000 tons a day. Of this amount probably less than 5% is consumed for generating electricity for all purposes. From the U. S. Census Reports for the year ending June 30, 1902, we gather the following approximate total current output and total station

	Dynamo Capacity Installed horse power	Total Yearly Output Kilowatt-hours	Estimated Load-Factor
Electric Light Station..	1 624 980	2 453 502 652	23%
Electric Railway Station	1 159 002	2 261 484 397	30%
Total.....	{ 2 783 982 { 2 075 000 kw.	4 714 987 049	26%

capacity of all electric light and electric railway stations. (The load-factors shown are obtained on the assumption that the maximum load was equal to the dynamo capacity installed.)

If all electric current had been generated by steam, the total coal consumption would have been less than 20 000 000 tons at the most (on a consumption of five pounds per kilowatt hour the total would have been less than 12 000 000 tons). This amount is insignificant compared with the 1 000 000 daily consumption for all purposes. Now if we consider the great available supply of coal and the extent of its industrial and domestic uses, and the fact that cheap coal will be one of the fundamental factors enhancing the industrial supremacy of this country, it is hardly probable that the cost of coal will be abnormally raised from the present level, except for the gradual increase of cost of mining and the increase in wages that might follow a general raising of prices for all labor and supplies and an abnormal rate of increase of production of gold tending to depreciate the money value. On the other hand, while we may not expect to obtain coal at a lower price than at present, and may probably have to pay more for it in future, it is also quite probable that though the new rotary steam-engine, *per se*, will not revolutionize the cost of power production, it will eventually lead us to the development of the rotary-gas-engine, which will make it feasible to realize enormous savings in the production of power. Therefore, while we may have momentary fluctuations of values of power, we are quite justified in expecting still further reductions for many years, before the curve of values of power shall have reversed its present lowering course and begun to climb.

This preamble was necessary to bring on the proper plane the discussion of the price of power assumed by the author. He puts this value at $34.00 per kilowatt per year. Let us assume that the equivalent of the total loads of all United States electric light and railway stations operated during the year ending June 1902 were grouped within a radius of 10 or 15 miles of the ends of four 518 750-kw. transmitting lines 500 miles long. On the basis of $34.00 per kilowatt per year the total power cost would have been $2\,075\,000 \times 34 = \$70\,550\,000$. This does not include the cost of distributing the power to the several consumers within the 10- or 15-mile radius.

Furthermore, the great bulk of the 25-cycle current would have to be converted to some other form before being used for the respective requirements, with attendant losses. Therefore the above cost would have to be increased by 10 to 20% for losses in transmission to and conversion of the 25-cycle current at the customers' sub-stations, plus interest, depreciation, repairs and taxes on lines, cables and subways, sub-station real estate and buildings, and sub-station transforming and converting apparatus, plus the labor and operating charges for the operation of the sub-stations. The aggregate of these items would

probably amount to about $22 500 000. For the sake of simplicity let us assume that this amount would offset the capital charges on real estate and buildings plus the labor production charges for the present steam generating stations. Then we should have left for direct comparison on one side the total cost of water power of $70 550 000, and on the other side the cost of fuel plus the interest and depreciation on the generating equipment, excluding real estate and buildings. It is estimated from the figures given in the Census Report that the electric stations paid for all kinds of fuel to generate their total output about 0.45 cents per kilowatt-hour, or $21 200 000 total.

The first cost of steam generating equipment in large stations, exclusive of real estate and buildings, making allowance for future reduction of cost of apparatus, can be safely estimated not to exceed $100.00 per kilowatt. The total cost of generating equipment for 2 075 000 kw. would amount to $207 500 000, and at the rate of 12.5% interest and depreciation, the capital charges per year would be $25 937 500. This added to the cost of fuel would make the total $47 137 500, to be compared with the $70 550 000 cost of water power. We therefore see that the $34.00 per kilowatt per year is excessive, and that on the basis of the operation of all the electric light and railway stations of the United States for the year ending June 30, 1902, the price should have been reduced to $\frac{47\,137\,500}{70\,550\,000} \times 34 = \$22.72$. An approximately identical conclusion can be arrived at by figuring the different elements of power cost from an ideal steam plant and comparing them with the corresponding costs of water-power; but it is not necessary to go into further discussion on this point. Therefore the price of $22.72 per kilowatt per annum for water-power transmitted 500 miles under the conditions given in the author's paper, the speaker considers an outside limit, as it would not give any financial inducement to the consumers to sacrifice the safety and reliability of control of the local steam plants in favor of long-distance transmission power with the attendant dangers of breakdowns met in the operation of such an extensive system of water-power generation and transmission —all depending upon the safety of a single pole-line exposed to all the dangers of weather, defective materials, or malicious acts of men. It is only necessary to mention these drawbacks, as persons familiar with the requirements of continuity of service in large systems will at once draw the proper conclusions.

If water power will ever be transmitted to large markets like New York, Chicago, etc., it will be necessary to keep at these centres an equivalent reserve steam generating capacity; first, for tying over shutdowns of the transmission power; and secondly, for taking care of a great proportion of the power required during the periods of heavy loads, thereby utilizing the water power for the 24 hours of each day with a load-factor of say 60% or over, and operating the steam plants at a very low load-

factor so as to save fuel. On account of the uncertain duration of shutdowns, storage-batteries could only be used to take care of the loads during the period of starting up the steam-generating plants.

P. G. GOSSLER: Mr. Torchio says that he considers the author's statement of power sold at $34.00 per kilowatt to be the outside limit; that he considers it necessary to sell power at about $22.00 per kilowatt or $17.00 per horse power to compete with the cost of steam. The speaker understands the author's price, $34.00 is for the sale of the power at the time of peak load. If Mr. Torchio's $22.00 per kilowatt is based on the average load-factor of 23%, as he gives it, and the power can be sold at about $97.00 per horse power, then the author is well within the limit. If the $17.00 per horse power is for the maximum the speaker fears that most of the water power companies would be forced into the hands of receivers if that price were maintained.

PHILIP TORCHIO: $22.72 was per kilowatt maximum and not per kilowatt average. That was arrived at by taking the dynamo capacity installed of all the lighting companies and railway companies of the United States to be equivalent to their maximum load.

P. G. GOSSLER: It is hardly fair to let the impression go out that the average price of power per horse power is $17.00. The speaker does not think it is based upon facts, the facts upon which commercial business is usually conducted.

PHILIP TORCHIO: The $17.00 per horse power referred to in the speaker's remarks is not the retail selling price of power delivered to the consumer. It only includes the interest and depreciation of machinery, exclusive of real estate and buildings, plus the cost of coal, which items the speaker assumed to represent the wholesale value of water power delivered at the purchaser's switchboard under the specific conditions of load factor, etc., given in those remarks. Nothing else is included in that figure. On the other hand, the selling price charged by a company retailing power will be dependent upon the use and the load-factor; and furthermore, in that price must be included a number of other items, as the production labor cost, the interest and depreciation, and taxes on real estate and buildings, and also on the distributing lines and subways; also the cost of distribution labor and repairs, and if it is a lighting company, the cost of supplies and maintenance of the customers' lamps; also it will include all the items of general expense that make up the total cost of power delivered to the customer, including management, accounting, canvassing, insurance, legal, medical, and damages, etc., and finally the charge for profit to the company.

J. E. WALLACE: Assuming that the mathematics underlying the curves given in Fig. 1 are correct, the speaker considers that a grave error in engineering judgment would be committed by

following them. To substantiate this statement, the speaker calls attention to a short press article written by him and published in a recent issue of the *Electrical World and Engineer*.*

One of the curves used to illustrate this article shows how the cost per kilowatt of energy delivered decreases with increased pressure. Beyond a pressure of 60 000 volts, in this particular case, the drop in the curve is hardly worth considering. The increased cost of insulators and transformers, due to increased pressure, is neglected in the curve; if included, it would ultimately overcome the slight drop beyond 60,000 volts and the curve would take an upward turn, locating economic pressure. Considering a factor for more reliable operation at lower pressures, the slight advantages gained in costs of delivered energy, as economic pressure is approached, do not warrant the very considerable increase in pressure.

With increase of output the cost of transformers is decreased to some extent, and the pole construction item decreases by a ratio that practically varies inversely as the output; possible failure of a line, however, should impose a limitation which would not allow the process to go on to an almost indefinite point. With a given increase in output the effect is to make economic pressure higher, as found by the author. Engineers agree that practical conditions govern theory, and it is held by the speaker that in deciding on the transmitting pressure to be employed, the advantages to be gained by increased pressure should again be compared with the factor for more reliable operation at a lower pressure, which factor naturally would increase with increased load for which a given pole line is responsible.

The conditions on which the curves in Figs. 4 and 5 of the author's paper are based are somewhat special; the total investment does not include the principal item of cost in a transmission scheme—the cost of the generating plant. Large profits could easily be figured under such conditions. The market price of delivered energy, and load-factor on both generating plant and transmission line, af well as cost of energy delivered to the line, are factors that have an influence on profitable efficiencies.

At the outset this paper claimed to be in the nature of a forecast of what might be done in the future. The author has said that a 12% profit is necessary to guarantee the bonds; it is presumed that the full issue of the common stock will be represented in the construction costs. The author does not give the proportion of stock to bonds, so we shall assume the usual proportion, 50% of each. Five per cent. for interest, and seven and a half per cent. for maintenance and depreciation are the figures given; they will be allowed for the generating plant. This means that one-half of the construction costs must earn 12.5% and the other half 19.5%, or an average of 16% on the whole; $10.90 is given as the amount that the generating plant will receive per kilowatt. Assumed that it does not cost more

*Electrical World and Engineer, Nov. 5, 1904.

than 90c. per kilowatt for attendance; we then have $10.00 repsenting 16% of the construction costs per kilowatt of the plant. $62.50 is an exceedingly small figure with which to pay for water rights, hydraulic developments, water-wheels, generating apparatus and the various other accessories necessary to a generating plant.

Watt-losses are considered in terms of a delivered kilowatt. It is apparent that if a line has 90% efficiency, there is a loss of 10% of the generated energy. Considering line resistance, it is also apparent that the annual conductor charges vary inversely as the per cent. loss; therefore the conductor charges are represented as a constant divided by the per cent. loss, thus $\frac{\text{constant}}{E^2\,(1\text{-}f)}$ where f equals line efficiency. At the other end of the line the relation of conductor charges per generated kilowatt to conductor charges per delivered kilowatt, is the same expression divided by the efficiency of the line; this gives $\frac{\text{constant}}{E^2\,(1\text{-}f)f}$ In other words, the conductor charges in terms of a delivered kilowatt vary inversely as the per cent. loss multiplied by the efficiency of the line. If one considers conductor losses in the per cent. of a delivered kilowatt, and neglects to consider that the delivered kilowatt is a function of the efficiency of the line, one is led into error. This error evidently led the author to Kelvin's law. With all due reverence to Lord Kelvin, the speaker contends that Kelvin's law does not deliver the cheapest kilowatt. At any practical pressure the error in Kelvin's law is, in the matter of a delivered kilowatt, rather inconsiderable; but the error multiplies and soon becomes formidable when it is carried into efficiencies for percentage returns. Anyone who cares to look up the subject will discover the truth of this statement.

M. H. GERRY, JR: A mathematical analysis of a subject of this kind has always seemed to the speaker to be of doubtful utility, not necessarily because of any defect in the process of reasoning, but because there are so many variables entering into the expressions. In order to apply such an analysis where the conditions are so far in advance of current practice, it is necessary to make arbitrary assumptions based on the judgment of the individual engineer; and the final deductions are so much affected by the assumed values as to render them little more than an individual opinion instead of being facts founded on mathematical reasoning.

Taking the author's expressions and modifying his assumptions, it can be shown that the economical limit of distance of power transmission in a given case may be either 100 miles or 1000 miles, and this being the case the mathematical development is of little value from an engineering standpoint as a means of predicting ultimate commercial results. This paper is, however, of considerable interest from its theoretical side. The mathematical expressions are in good form, and will prove of value in the future when more is known of the physical and

commercial conditions surrounding the transmission of energy at the excessively high pressures and great distances referred to. At the present time the information before us regarding pressures above 100 000 volts is so limited as to make substitutions in the various mathematical expressions of very doubtful value; it is certainly not wise to attempt to show in this way the limitations of distance for future electrical transmissions. Such statements are misleading and should not appear unchallenged in the PROCEEDINGS of the INSTITUTE,

A. E. KENNELLY: We are indebted to the author of this paper for a careful analysis of the problem of the commercial limits of electric power transmission under clearly specified conditions. There is no pretence that these conditions are immediately available for general estimates. The pressures are much in excess of those in commercial use to-day, and the power assumed is also much greater than the power ordinarily transmitted. Nevertheless, the solution of the economic problem for definitely assumed pressures and kilowatts is perfectly proper matter for discussion, as an abstract proposition, quite independently of the question as to when such pressures and powers will be practically available in the future.

The history of electric power transmission in the past shows that it is unsafe to prophecy the commercial limiting distance of transmission. In the early days of the development of the incandescent lamp it was demonstrated mathematically that it would be commercially impracticable to transmit electric power to such lamps more than a few hundred feet. The proposition was valid at the time, but only for the conditions then existing. The three-wire system and the 100-volt lamp upset both the assumptions and the conclusions. The practical men carried power to lamps distant several thousand feet from the generator. Then the transformer became known and it was demonstrated that it would be commercially impossible to transmit power more than a few miles. But improvements in construction invalidated the assumptions of this proposition also, and the practical men have now succeeded in carrying power commercially to a distance of 230 miles in California at a pressure of about 60 kilovolts. The conclusion of the author's paper is that under the conditions he has assumed, power may be carried about 500 miles and pay a profit, if the block of power is large, say 200 megawatts. This conclusion is interesting, because it would place both New York and Chicago within the sphere of influence of Niagara Falls. But a yet more important deduction in the paper is that when power is transmitted in such bulk as is considered in the paper, it pays to use copper wires so large that even at 170 kilovolts between them, there will be no dissipation of power by brush discharge. In other words, aluminum wires will not be rendered necessary for long distance transmission of large blocks of power, since the copper wires would have sufficient diameter to keep the electric gradient in the air down to the safe working value and below the smashing point.

Curiously enough, the distance the author arrives at (500 to 600 miles) is about the same as that to which telegraphers generally carry their small amounts of power over wires for transmitting messages. For distances exceeding 500 or 600 miles they usually insert a repeater.

CHARLES F. SCOTT: The author's paper is the outcome of several years of study of the problem of long-distance transmission in which he has dealt with it in various ways. Several years ago he did some excellent work in determining experimentally in Colorado, on a circuit of the Telluride Power Transmission Company, the loss through the air between wires at low pressure. The curve representing this loss shows that it is extremely small under the conditions which the author employed until approximately 60 000 volts was reached, when the curve took an upward turn and a slight increase in pressure caused a very great increase in loss. It was evident that a pressure much above 60 000 would cause a loss so great as to be prohibitive. The wires which the author used were small in diameter. The critical point at which loss begins occurs at a higher pressure when the wires are of greater diameter. This matter was admirably set forth in Professor Ryan's paper before the INSTITUTE about a year ago.

The author now considers the general problem of power transmission from the commercial rather than from the scientific side, and one may readily imagine that the problem was one which grew larger and larger as he worked upon it, for the paper shows the result of painstaking labor. Nearly all of the papers which are written upon transmission deal with certain specific elements and do not take up the subject in a broad way. At the International Electrical Congress, for example, there were many papers in the Transmission Section, but these papers dealt with specific or with local matters such as details of construction, types of insulators, characteristics of conductors, methods of operation and the like. There was no broad general paper, except one which was read by title. That paper was prepared by an official representative to the Congress from the INSTITUTE and it is the paper which has been presented to us this evening.

Some objection has been raised to the use of specific figures by the author. The particular value of the paper is found in its treatment of a general engineering problem and in the bringing together and showing the relation between the various elements which enter into commercial power transmission, The paper, however, would lose much in interest and in value if it presented simply the formula showing the relation between various variables and constants without assigning definite commercial values. These values are of course liable to change, but the whole matter assumes a much more definite, and satisfactory condition, if in addition to the abstract relationships there are given also the concrete values which result when certain reasonable values are given to the different quantities.

involved. It is, for example, a satisfaction to know that under conditions which are fairly commercial the distance from Niagara Falls to New York City is not beyond the limits of commercial possibility.

This paper deals with something outside of the range of electrical operation with which we are familiar. If we were to refer to the wire tables of 15 years ago we would find that the units then used were 16 c-p. lights and that the distance ran up into a few hundred or a few thousand feet. Electrical work at the present time is on a much larger scale, and the present paper goes far beyond our present needs. The curves give little attention to units less than 50 000 kw., which is about the output of the largest stations which are now in operation. Many of the conditions set forth in the present paper do not apply to less than 200 000 h p., which is probably about the amount of electrical power used in New York City. The field of power transmission which is considered in the present paper is therefore one which does lie in the present, but which we may encounter a decade hence. It gives us a vision of the electrical future.

An interesting point may be noted relatively to the percentage of loss in transmission. Most of us would probably estimate the desirable loss in transmission over considerable distances at 10 or 15%. The curves in the present paper show that for 100 miles the economic drop does not exceed more than about 5% and that for less than 100 miles the loss would be considerably smaller. Up to even 200 miles the losses on the curves representing all the conditions considered do not exceed nine per cent.

High pressures have usually involved the idea of a small wire, and in some of the earlier transmission systems the limit of the size of wire was fixed not by its conductivity but by its mechanical strength—electrically the conductor could be made smaller than was made necessary by the requirements of mechanical strength. The present paper shows that we have gotten into a new order of things in power transmission on a large scale, as the size of wire for economic transmission for large power at high pressure is so great as to bring about the surprising result that the atmospheric losses which have been assumed to be the determining element in high pressure transmission no longer determine the maximum pressure; the size of wire required at a given pressure to insure economic transmission is so great that the atmospheric losses are avoided.

C. L. DE MURALT: 'In the author's paper the fact stands out prominently that it is in all probability the economical side of the problem and not the technical side, which determines the distance to which energy may be transmitted electrically. Let us therefore look more closely at the economical variable of his equations.

The author has taken the price of $34.00 per kilowatt per year

as a selling price for the transmitted energy. In Switzerland, which may be called the power transmission country par excellence, electric energy is sold in most cases at about $20 per horse power per year, or approximately $30 per kilowatt per year. But you know that coal is very high in Switzerland—it is here about $2 per ton, and there $6 or $8—if therefore in Switzerland competition of coal has to be met by selling the kilowatt per year at $30, it would seem difficult to obtain $34 in this part of the world where fuel is so much cheaper. The author's curves, notably Fig. 5, show very nicely how the maximum distance, over which energy can be economically transmitted, may be increased by increasing either the amount of energy transmitted or the pressure of transmission, or both. But if in his curves the selling price is reduced to what it will have to be to compete with coal, then the distance of transmission will in a great many cases be materially decreased, no matter how large the amount of transmitted energy or how high the pressure of transmission. If, for example, conditions are taken as they are now around New York it would seem doubtful if this distance would be more than half of that shown in Figs. 4 and 5. This is the point the speaker wishes to bring out.

RALPH D. MERSHON: The difference of opinion which has developed here to-night is no greater than was to be expected. Probably there never were two engineers who estimated in exactly the same way on everything, or whose estimates on a proposition, if examined in detail, would agree exactly; one man would be higher on one item and lower on another, although the total estimates made by them might agree very closely. Moreover, in making estimates, it is not an uncommon experience to have the figures on some details higher and on others lower than the figures actually obtained in the construction for which the estimate was made; the result being an equalization of the positive and negative errors, and the total estimate comparing very closely with the cost of the completed work. Such a condition of affairs does not argue any lack of skill in estimating, especially on work along new and untried lines, and the engineer is legitimately entitled to such equalizing chances as those mentioned.

This paper, in so far as the numerical values are concerned at least, represents simply a piece of estimating. In considering the numerical values of the paper, therefore, too much stress should not be laid upon details. The principal consideration should be given to the work as a whole.

On the different items of the paper there will be differences of opinion among engineers, both as to assumptions and numerical values; but the average opinion, if one could get at it, would probably come very close to the figures given in the paper.

Suppose, however, that there were errors in the paper sufficiently great to cause an error in the limiting distances de-

duced, as great as 20%. Even with that error the value of the paper, as giving a general view of the subject, would not be diminished to any considerable extent.

As Mr. Scott has said, such a paper as this is more interesting with some definite figures than if it gave simply an analysis, and hence the numerical values were introduced. No exceptions worthy of notice have been taken to the method of analysis employed.

The two extremes that Mr. Gerry mentioned, namely, 200 miles and 2000 miles, between which the limiting distance of transmission might fall, are pretty far apart. Probably the idea that Mr. Gerry means to convey is that the conditions under which a transmission might be undertaken might vary so widely in different locations, especially as to the cost and selling price of power, as to render very uncertain the limiting distance when treated as a general question. But, as the paper shows, the limiting distance of transmission will, among other things, depend very greatly upon the total output of the plant, the distance being greater for greater outputs. Now the assumption of a large market and a large source of power to supply it narrows the location of the transmission very considerably, and this in turn fixes the values of cost between narrower limits than those which Mr. Gerry probably has in mind.

In this paper there is done, in a general way, just what Mr. Gerry does when he estimates on a particular plant. He takes a specific case and makes an estimate. The speaker has tried to make the estimate in a general way; that is, instead of considering various plants separately and undertaking to work out something for each one, by means of formulas the problem is put in such shape that by working out a comparatively few values, results can be obtained for plants whose outputs cover a considerable range, thus enabling one to get a much clearer idea of the trend of results as the various quantities are varied.

Mr. Stott brought out a number of interesting points, one of them the question of the sale of power on a flat rate; another, the consideration of the load-factor. But in this problem there is no need to consider the load-factor, or any charge except the flat rate, for the reason that no matter what the load-factor or what the price we may sell the power for, there is always a certain peak and certain income; divide the income by the peak, and you have a certain flat rate. That is the figure which must be considered in a problem of this kind, for the reason that in the water power plant—which we are necessarily considering—there is practically no variable factor. In the steam plant there is a variable factor, the cost of fuel. In a water-power plant it costs practically the same per kilowatt whether you deliver one-quarter of the output or the whole. It makes little difference what proportion of the

full capacity is carried; some, perhaps, but not enough worth considering in a paper of this sort. Mr. Stott also spoke of the question of carrying the peak load. The problem does not necessarily assume that the peak load will be carried. Take the case of bringing power to New York City. There are pretty large steam plants here. It would be cheaper, in general practice, to carry the peaks on these steam plants and get a more uniform load on the water-power plant, which would enable the purchaser to pay a higher price per kilowatt per year than otherwise.

As to the cost of the generating plant, as represented in he price assumed in the figure for cost of power, it is low; but not impossibly low. There are some water powers throughout the country where the cost of the plant, and therefore of the power, is very low, because of advantageous physical conditions. But aside from that, supposing the development to be similar to that at Niagara Falls; in the case of blocks of power as large as those considered and as more power plants are installed, and more skill and experience is brought to bear upon them, the cost of power from such developments will be very considerably diminished from what it is now. Mr. Stott brought up the question of higher frequency in order to get better power-factors, but there are a good many arguments against that. If the load were very well distributed, along the transmission line, higher frequency is a matter which might be worthy of consideration; but generally the load is bunched at the end of the line, and in such cases the lower frequency would undoubtedly be preferable.

Mr. Torchio's contribution is a very interesting one, but there is so much in it that one can not follow it closely enough, hearing it for the first time, to reply to it. After reading it more carefully, the speaker may perhaps reply with a written communication. The cost Mr. Torchio has taken for power is remarkably low, certainly lower than any that the speaker has investigated. The criticism which Mr. Torchio made in regard to assuming one cost for the power produced is, from some standpoints, a legitimate one, although if he will turn to page 781, in the middle of the page he will see a paragraph which deals with this question and calls attention to a compensating factor. The reason for taking one cost of power was simplicity. The aim was to determine the maximum distance to which power could be transmitted, and with that in view perhaps the curves of small output should have been omitted. But they are of interest in connection with the compensating advantage, mentioned on page 781, which will have some effect. The power cost assumed, therefore, is that which would best apply to very large outputs, to those large outputs determining the maximum distance of transmission. As Mr. Torchio can see, it would complicate the equations still more to introduce a variable factor in the cost of power.

Strictly, the proper method of applying the equations is to start with a certain cost of power, and a certain sale price of power, and determine how far it could be transmitted. In that case there might be a different cost of power and different selling price for each size of plant.

Replying to Mr. de Muralt, in regard to power prices in Switzerland: he should bear in mind that as a general thing apparatus, labor, and money are cheaper in Switzerland than in this country.

In regard to the question of bonds mentioned, 5% interest was assumed on the actual investment, and 12% of the investment taken as profit. That does not mean necessarily that the bonds should be rated at 5%, or issued on the basis of returning 5%. It means that the return has been divided into two amounts, one 5% and the other 12%. The total return is 17%, and you can divide it between dividends and bonds as you please.

As regards Mr. Wallace, his quarrel seems to be with Lord Kelvin, in which case no reply is necessary. Mr. Torchio will find, if he carefully examines the equations, that the Kelvin law has been given full weight and has been modified only by those elements of cost of transmission affected by change of pressure.

RALPH D. MERSHON (by letter, after adjournment): Mr. Torchio has criticised the assumption of the same cost of power for plants of all capacities; to this the writer has already replied. But in addition, Mr. Torchio discusses the question of squeezing a little more power out of a generating plant to make up for the line loss, and the possibility of obtaining this increment of power at a lower cost than the bulk of the power produced by the station. The writer cannot agree with his argument, even if it be made on the assumption that the same company owns both the transmitting plant and the generating plant. In the case of a generating plant of a given capacity, the cost of power produced by that plant would be computed; and for any increased output, no matter how great, there would be computed the corresponding cost in accordance with the law governing the variation of such cost with output. Why the law of variation should be any different for large or small increments is not quite clear to the writer. The fallacy of Mr. Torchio's argument can be shown by carrying it a little further. After having obtained 10% more by the method he advocates, why not obtain another 10% by the same squeezing process, and so on to any amount of power required?

Touching the drop limitations mentioned by Mr. Torchio as imposed by the various kinds of apparatus, the writer believes that the limitations in this direction, due to synchronous apparatus, will be removed in the near future. The assumption that large numbers of synchronous converters must of necessity be used is not in any case in accord with the writer's ideas on

the subject. He believes the time will come when there will be little use for synchronous converters, alternating currents being used for almost all industrial purposes.

There is a point in regard to the transmission line which Mr. Torchio has overlooked; namely, that the paper assumes three transmission lines. Perhaps it is not so clearly stated as should be that these three are distinct and separate and on separate structures, but such is the assumption.

The writer has not at hand the data for entering into a discussion on the probability of an increase of fuel costs. The statement that the value of power will increase was based partly, but not wholly, upon this consideration. The writer believes it is generally deduced by statisticians that it will not be very long before the price of fuel will increase to a point where it will be seriously felt; this of course being due, not only to the diminution of the source of supply, but also to increase of population and its increased demands for fuel and the materials whose production involves its consumption. But there is another reason why the value of *electric* power will increase, and that is that as the delivery of such power becomes more and more reliable, the price will be regulated, not, as now, by the consideration of supplying power to a customer who has a duplicate steam plant, the fixed charges on which must be carried, but on the basis of supplying a customer who has no steam plant except such as is necessary for carrying his peak. Carrying the peak by steam will make it possible for the purchaser to pay a higher price for water-power than he otherwise would, and yet result in a lower total cost of power to him than though he carried the whole load by steam. This question of a combination plant would, if considered by Mr. Torchio, compel him very materially to modify the figures of his general and very interesting discussion as to the selling price of power.

The writer questions very strongly the statement made by Mr. Torchio, that it is necessary to carry " equivalent reserve steam generating capacity " in the case of transmitting power to Chicago or New York. A certain amount of reserve may have to be carried to provide for extreme emergencies, but the writer thinks that in time the amount of such reserve will be more and more reduced. This has been the experience with transmission on a smaller scale, and the writer sees no reason why, as the art advances, it should not be the case even in a greater degree with larger enterprises.

Referring to Mr. Wallace's statement, as based upon some figures he has made for a specific case, if he had selected a plant of an output or distance of transmission differing from that assumed by him and had applied the same criterion as he has applied to the question of economical pressure, he would have arrived at a different pressure for each output and distance; in other words, he would have obtained results resembling those in the writer's paper.

Regarding the question of the figure assumed for the cost of power ($10.90 per kilowatt at the step-up transformers), the assumption made is a possible one, commercially. The best proof of this statement is that power has been and is being produced for less than the price named. Some of the members present at the meeting at which the writer's paper was discussed could, if they had felt at liberty to do so, told of power being produced at a considerably less figure. It is well known that, in a city not very far from New York, power is sold at $15 per horse power, this price to fall to $14 when the total load shall exceed 10 000 h.p. This power is transmitted from a water-power 85 miles away, and is sold at a profit. One can, if he chooses, figure back and determine roughly what the power must cost at the terminals of the step-up transformers.

If any one desires to purchase power at the point of generation for $10.90 per kilowatt per annum, he can perhaps be accommodated up to 200 000 h.p.

In view of the discussion which has taken place in regard to the selling price of delivered power, the writer purposes to plot another set of curves which will apply to a lower selling price than that assumed in the paper, and shall include them in the paper with the curves applying to the selling price of $34 per kilowatt already assumed.

In the numerical calculations of the paper, which are long and somewhat involved, there crept in an error in the cost of synchronous motors, although extreme pains were taken to have all figures carefully checked by two or more persons. In the final printing of this paper in the TRANSACTIONS of the INSTITUTE, this error will be corrected. The correction will modify the distance curves, Figs. 4 and 5 already given, by increasing the profitable distance of transmission under the conditions assumed; it will not change the other curves.

Discussion on "The Maximum Distance to Which Power Can Be Economically Transmitted," at Pittsburg, Pa., January 9, 1905.

S. M. Kintner: The author has given us a paper that is exceedingly broad in its scope, so broad that few, if any, are in a position to check it. The author has probably got more good out of the paper than any one else, in the very thorough investigation that was necessary for its preparation. In saying this it is not intended to detract from its value, for it is the belief of the speaker that this paper will prove of great value to more of us when we learn more about the constants involved and when higher pressures and larger powers are used commercially. The author has committed himself to but few engineering points, but some of these involve quantities of such magnitude that one is astonished in considering them, yet that is no reason for condemning the paper.

Such high pressures, which are now looked upon as abnormal commercially, and such large sized plants, also far beyond anything known in present practice, may bring about changes in design that will readily take care of present anticipated troubles. There is always great uncertainty in drawing conclusions from curves extended far beyond the observed values, for the curve is just as liable to go down as up. The author's range of constants will provide considerable latitude.

Though there may be many points of detail upon which one may not agree with the author, yet it is the opinion of the speaker that a thorough study of the paper will repay one and give a broad view of all the most important elements considered, a view so broad that corrections can readily be made from time to time, as experience dictates.

P. M. Lincoln: It seems to the speaker that the author's deductions are open to considerable criticism. He has developed a number of laws for costs of the various elements which go to make up a transmission line, and these laws are expected to hold true for an amount of power up to at least 500 000 kw. and pressures up to at least 200 000 volts. These limits are far beyond anything which is in existence to-day. The speaker does not believe that the author, or anyone else, can say what will be the law of variation of costs for these elements at the pressures and outputs with which he deals. For instance, the author assumes the variation of cost of insulators to be as a cube of the pressure; this assumption may hold with the pressures in use at present, but how does the author know that it will hold when pressures are increased to 150 000 or 200 000 volts? The law of variation of sizes of cost of transformers is also given: how can he tell that it is going to hold for the large powers and high pressures?

The author has figured upon using synchronous apparatus at various points of the line for the purpose of maintaining unity power-factor; the desirability of using such devices as

this is as yet a mooted question, nevertheless they are incorporated in the general scheme when considering the subject of cost of long-distance transmission.

The right of way is taken as simply proportional to the distance of transmission. Evidently a factor depending upon the amount of power should also be included, as well as something to determine the density of the territory which is to be served. This later is a very considerable element.

It has been remarked that the author has paid no attention to the matter of load factor. His assumption of buying power at a fixed figure eliminates the question of cost of generating plant, and in dealing with the transmission problem only the load factor of course may theoretically be neglected. The complete problem should, however, take into consideration the cost of generation of power as well as its transmission and distribution, for in the cost of generation the load factor is one of the most important factors. Strictly speaking, the author is dealing simply with a transmission problem and therefore the matter of load factor may be omitted.

MR. SKINNER: On the author's assumptions of number of units and ultimate output of station, the size of transformer unit required would be 30 000 kw. at 200 000 volts. A single transformer of this capacity would have power approximately equal to that of the first Niagara station. The largest size of transformer with which the speaker has had anything to do is of 3000 kw. capacity. In the manufacture of large transformers one of the most important things to be considered is the mechanical construction of the high-pressure coils. In ordering insulating material for the 3000-kw. transformer, the manufacturers were asked to install larger machinery, as they had no machines of suitable size to manufacture the insulating material required for this size of transformer; size of coils and insulation are not insurmountable obstacles in the way of making larger units, however, as it is possible to piece the various parts that enter into this construction. The speaker admits that at the present time he is unable to imagine the construction of a 30 000-kw. transformer for 200 000 volts. A different general design of transformer must be perfected before the larger sizes can be built successfully.

Another interesting phase of the author's paper is that referring to line insulation. In the opinion of the speaker, the line construction is one of the simplest parts of the problem; this part of the problem can finally be solved by the introduction of steel towers and as few insulators as possible.

H. W. FISHER: Unquestionably this paper is an excellent one and shows much thought and careful mathematical deduction. Without attempting to consider the mathematical side of it, the speaker is of the opinion that the price charged per kilowatt per annum, namely, $34.00, may be higher than that which large users of power would be willing to pay.

In connection with the author's paper, comes very naturally the question: what will be the limiting maximum pressures which can be operated on underground electric cables? The speaker has designed and made short lengths of cable which have withstood 150 000 volts; this also has been accomplished abroad. The lasting qualities, however, of very high-pressure cables can only be determined by operating them under practical conditions for long periods of time. On account of the much greater stress on the insulation near the surface of the conductor, the greatest care has to be used in the design of cables for high pressures. The speaker has made a calculation that will illustrate this point. Suppose there are two cables consisting of No. 6 and 0000 B. & S. gauge solid conductor, homogeneously insulated with 0.1875 in. of good insulating material. If these cables are subjected to 10 000 volts, the stress on the insulation near the conductor will be:

1608 volts per 1/64 for the No. 6.
1138 " " " " No. 0000.

The stresses on the insulation near the lead will be:

485 volts per 1/64 for the No. 6.
627 " " " " No. 0000.

Here we see that the insulation of the No. 6 is subjected to a much greater stress than that of the 0000, and practice demonstrates that it is more difficult to make small conductor than large conductor cables for high pressures. It will also be noted that the insulation of the No. 6 near the conductor is subjected to more than three times the stress on the insulation near the lead. Theory also shows us that if 7.73/64 in. of insulation be applied to the 0000 cable, the insulation near the conductor will be subjected to the same stress as that of the No. 6 above; namely, 1608 volts per 1/64. It would appear, therefore, that a No. 0000 cable insulated with 8/64 in. would be stronger than a No. 6 with 12/64 in. Referring to the first mentioned cable, 14 120 volts on the 0000 cable would produce the same dielectric stress near the conductor as 10 000 volts on the No. 6 cable. For stranded conductors, the stresses near the conductor may be from 20 to 30% greater than those for solid conductors of the same area.

To compensate for this unfortunate condition, two things may be done: first, place near the conductor insulating materials of great dielectric strength; secondly, use insulating material the specific inductive capacity of which will be greatest at the conductor and which will decrease toward the lead cover at the right rate to make the dielectric stress the same all over the insulation. The speaker mentions these few points because they are of the utmost importance in the correct design of high-pressure cables. It is scarcely probable that underground cables will ever be needed to withstand as great pressures as conductors placed on the best insulators. Transmission over long distances will generally be done by the latter plan, but if

the pressures are very high, cables operating from the secondary of step-down transformers will no doubt be used in city limits. Connecting long lengths of aerial conductors to long lengths of cables is not desirable because of danger to the cables from lightning and resonance.

N. J. NEALL: A value should have been inserted in the equations having for its base the probable loss due to interruption of service; uninterrupted service will undoubtedly be more and more demanded, and the proportional cost of interruption of service by lightning-arresters will become greater.

If one were to think of a 500-mile line running, say, from Buffalo to New York, such advanced line construction might be conceived of as to enable one to estimate the cost of maintenance confined to general wear and tear only, but lightning disturbances would certainly be more numerous per line, although possibly not much greater per length of line. Even with simpler lightning-arresters there seems no reason to abandon our theories concerning their functions. For this reason we should consider the recommendations made by Mr. A. J. Wurts—that a line should fairly bristle with discharge-points. This for a high-pressure, high-power line would perhaps mean the employment of section-houses where lightning-arresters could be installed and where section-foremen could live and have apparatus for keeping the line intact. The telephone for such a plant must receive careful installation; it might perhaps prove inadequate and would have to be supplanted by wireless telegraphy. These factors seem worthy of consideration in such a discussion and their bearing on the cost of transmission might assume a value which would materially change the figures given by the author.

DISCUSSION ON "THE MAXIMUM DISTANCE TO WHICH POWER CAN BE ECONOMICALLY TRANSMITTED," AT PHILADELPHIA, PA., JANUARY 9, 1905.

WM. MCCLELLAN: The chief value of the author's paper is its exposition of the methods used. So far as results are concerned, there will be widely differing opinions. The speaker believes that the author has been very liberal except in what might be called the factor of safety. Apparently, three circuits have been provided, each with one-third load capacity. If one of these nine wires should fail only two-thirds of the rated load could be carried. We have, however, plenty of reserve in the converters, etc. In a line projected some time ago there was one extra wire provided for emergencies. The provision in this respect does not seem quite consistent. On the other hand, one must remember that these conductors are of solid copper, one inch and a half in diameter, and not likely to get in trouble except in the land of cyclones.

One should naturally ask, does the paper settle anything definitively? It does tell us definitely that when we have our wire large enough to suit our economic conditions, it will be plenty large enough to suit our electrical conditions. When we heard of Professor Ryan's paper last February, we thought that we might have to increase our wires above economic diameters in order to prevent coronal loss, but we are sure now that we shall not have to do so.

At present there are so few cases where we shall have to transmit such large blocks of power over such distances that the speaker does not believe that the problem is of great interest to many men. A more interesting problem, and one that is becoming more and more prominent, is the combination and development of the many small water-powers in various localities. In many cases these are separately worth little, but taken together, and properly developed, they become dividend earners. Some time ago a commission was examining all the water-powers of New England for this very purpose. It seems almost certain that a great deal of our future transmission work will move in this direction; it will become a part of our future railroad development.

A. B. STITZER: The speaker knows of one company installing some high-pressure apparatus where there are two cables to each station. Either cable is large enough to carry the station's full load, so that if one cable breaks down the load can still be carried with less than eight per cent. drop; the two wires working together will give one half this drop.

Most of the speaker's experience has been with underground transmission work; 13 200 volts is high enough for underground transmission. The insulation is 0.0219-in. paper around each conductor and 0.0219-in. paper over all. In the power house we use 0.375-in. rubber. We were using 0.3125-in. rubber but that is hardly sufficient. The paper is treated with compound; it

is three-conductor cable with 0.09375 inches of lead on the outside.

CARL HERING: The author bases his figures on the present cost of steam power in cities, but it seems to the speaker that there are prospects of reducing the cost of power from coal quite appreciably. Take the case of steam turbines, for instance. A few years ago very little was known about them; with continued improvements the steam turbine has progressed wonderfully. If further improvements are made in the future, electrical transmission of energy may not be as able to compete then as it is now. It seems to the speaker that there are so few cases where power would be transmitted to such enormous distances as 500 miles that each case must be figured out by itself, and that any such general laws are of little use.

H. A. FOSTER: The speaker believes he is correct in saying that the best steam turbine has not reduced the cost of steam power below the cost at full load of the best of reciprocating engines. Below full load the steam turbine has somewhat reduced the cost of steam power, but at any time a slight increase in the cost of coal will effect all the economies produced by such methods.

Most of us who have had to deal with electric light stations or railway power plants have the matter of the load factor before us all the time. With large water powers the speaker thinks the load-factor of little moment, because there are other loads that come on during the day, many of them that make the load factor nearly 90. A few years ago, at Niagara Falls, the load line could be drawn with a ruler. At that time the lighting load was hardly noticeable.

APPENDIX.

REPORT OF THE BOARD OF DIRECTORS

FOR THE FISCAL YEAR ENDING APRIL 30, 1904.

The Board of Directors presents herewith for the information of the Institute a report of its work during the past year, also of the financial standing of the organization.

The Annual Convention for 1903 was held at Niagara Falls, June 29–July 3 and was notable for the importance of the papers presented, the thorough discussion, and the attendance of nearly 500 members and guests, practically double that of 1902.

The phenomenal growth in membership has continued, and the total has now passed 3000. The accessions continue by reason of the increasing appreciation of the work of the Institute, through the efforts of the Committee on Increase of Membership, supported by the co-operation of those already upon the roll in making known the advantages of being identified with the Institute. Through the establishment of Branches in many important cities, electrical engineers throughout the country have been brought into closer relations with the work of the Institute, and the Committee on Local Organizations points out the beneficial results of this practice. Most of the committees have presented reports of their year's work, and brief abstracts of these show the general progress made.

Committee on Papers.—Seven meetings have been held for which arrangements have been made by this committee, although with two exceptions the number of papers has by request been limited to two in order to allow more time for discussion. Of the 17 papers, four were voluntarily submitted by the authors, while 13 were prepared at the request of the committee. Papers are more readily obtained when a specific subject is suggested, and the diverse interests of the personnel of the committee have facilitated more intelligent work in this direction. This has also led to the organization of the discussions which have been more spirited and valuable. The holding of Branch meetings has also led to the accumulation of additional material which in many cases is of great importance, due to the practical experience of members working under varied conditions in different parts of the country.

The Editing Committee.—The duties of this committee have been largely increased by the great increase of matter from Branch meetings. It has also brought about the printing of papers in the monthly editions

sufficiently in advance of meetings to enable members to prepare themselves to discuss them intelligently, and also permit those who are at a distance to send in contributions to discussions so that they may be read, or incorporated in the printed record.

Finances.—An important change in the care of funds has been made by this committee. As will be seen by the Financial Report, separate bank accounts have been established representing certain funds which are drawn upon only for the specified purpose of said funds. In order to carry out this plan it was necessary to convert into cash seven $1000 U. S. bonds held by the Institute from which $7,409.37 was realized. These funds as well as the current bank account of the Institute are now deposited with the Mercantile Trust Co., and Farmer's Loan and Trust Co., with the exception of $8000 in U. S. bonds which remain in a safe-deposit compartment of the Colonial Trust Co. The existing condition of the Institute's finances appears elsewhere in this report. The form of this statement having now been standardized it has become practicable to print opposite nearly every item, the corresponding figures of the previous year for the purpose of comparison. The Secretary has had this innovation in view for some years past, but was unable to introduce it until now, on account of certain changes in the form of the statement.

The ordinary receipts of the Institute during the year ending April 30th, 1904, were $40,986.78. This amount was made up of $32,724.12 from members, including entrance fees from Associates and transfer fees from Members; $1203 in students' dues, and $7,059.66 from advertising and miscellaneous sources. The ordinary operating expenses of the Institute were $36,394.20, leaving a balance of ordinary receipts over expenses of $4,592.58.

Owing to the fact that for the year ending April 30th, 1903, disbursements properly chargeable to the Carnegie Fund were paid out of ordinary current receipts to the amount of $1,312.20 the balance for that year should properly stand at $1,933.78 instead of $621.58. It should also be noted that the sum of $541.62 paid out of ordinary receipts for the year ending April 30, 1904, for the expenses of the Land, Building and Endowment Fund Committee, should properly be charged to that fund, making the true balance stand at $5,134.20 instead of $4,592.58. On the other hand the Life membership receipts for 1903 were $600, and for 1904 were $200, neither of which sums should appear in this column except as a matter of bookkeeping. The true relative difference in the balances of operating receipts and disbursements to April 30th for the years 1903 and 1904 respectively should be $1,333.78 instead of $621.58 and $4,934.20 instead of $4,592.58 as corrected by this explanation. Adding to $3,600.42, which is the difference between these balances, a gain in accounts receivable of $1,485.78 for the year ending April 30, 1904, makes the total net gain for 1904 over 1903 $5,086.20.

The bank balance available for current expenditures on April 30th, 1904, was $7,861.44. Adding this sum to $8,875.63, the market value of the United States bonds owned by the Institute makes a total of $16,737.07 in cash or its equivalent. Subtracting from this amount $4,400, as due to the Life Membership Fund, gives a net balance of $12,337.07 in cash or its equivalent immediately available for any ordinary or extraordinary expenditure of the Institute.

The accounts payable on April 30th, 1904, were $246.44 against which were accounts receivable amounting to $9,893.42, consisting almost entirely of arrears in dues, but not including any debts owed by members suspended or dropped for non-payment of annual dues. During the year the plant of the Institute was increased by the purchase of Transactions, library books and fixtures, and office furniture to the extent of $3,523.19 all of which was charged to current revenue.

The inventory valuation of the Library has been increased over the amount reported last year by $12,300.38 for the reason that statistics were not available at that time to show its actual value. It has since been appraised by a special committee and the amount of $21,737.13 accepted as satisfactory.

The Board of Examiners.—All applications for transfer from the grade of Associate to Member, for election as Associates, or for enrolment as Students, are considered by the Board of Examiners. Ten meetings have been held, and a grand total of 1042 applications have been reported to the Board of Directors as follows:

	Recommended.	Not recommended.
For Transfer	43	26
For Election as Associates	649	7
For Enrolment as Students	313	4

Committee on Increase of Membership.—The record of an increase of membership by the election of 798 Associates is a sufficient indication of the work of this committee in the past, but it is still engaged in its efforts to reach the very large number of eligible electrical engineers who will no doubt appreciate the benefits of membership when the matter is properly presented to them. It believes a systematic canvass may yet be made through the branch organizations which will be of great service to the Institute.

Local Organizations.—The Institute Branches have been increasing in number and in interest. There are at present, 29, of which 15 are in cities, and 14 are student meetings in technical schools. The average aggregate attendance at these meetings is 1250 (about 400 being students.) The Branch meetings are reaching our members and the young men who are to be the future electrical engineers of the country, in a way which enormously increases our activity and our influence.

The Report of the Committee on Local Organization, based upon reports from the branches, is appended to this report. It shows a remarkable development, a sustained interest, and encouraging prospects for the future.

International Electrical Congress.—While the actual organization of the Congress has been carried on independently of the Institute, there has been continued and harmonious co-operation, which it is believed will lead to the best possible results. The Institution of Electrical Engineers will be the official guest of the Institute, while all foreign delegates and members of various foreign electrical organizations will participate in the circular tour, arranged by the International Electrical Congress General Reception Committee and the Committee on Transportation and Arrangements. The itinerary as planned provides for brief technical visits on the way to St. Louis by the Northern route, including Boston, New York, Schenectady, Montreal, Niagara Falls, and Chicago, also

Pittsburg, Washington and Philadelphia upon returning. The stay at St. Louis will cover the week of the Congress, September 12–17, during which the Institution of Electrical Engineers will hold a joint meeting with the Institute. The Congress subscribers now number about 1300, and 150 papers have been promised which are to be published in three volumes.

Cadmium Cell.—In accordance with a resolution adopted at the Niagara Falls Convention, a committee appointed to report upon the adoption of a standard cell has prepared specifications, and suggests that it be given the name "Weston Normal Cell." It is understood that this matter will be submitted to the International Electrical Congress, and that the cell will become a universally recognized standard.

Union Engineering Building.—This project which was brought before the Board of Directors and the Annual Meeting a year ago, has assumed a different form owing to the declination on the part of one of the national engineering societies to enter into it. This made it necessary to obtain from Mr. Carnegie his assent to a renewal of his offer to the other societies, which he did, increasing his gift by 50% as shown in the following letter:

GENTLEMEN OF THE AMERICAN SOCIETY OF MECHANICAL ENGINEERS, AMERICAN INSTITUTE OF MINING ENGINEERS, AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS, AND THE ENGINEERS' CLUB OF NEW YORK:

"It will give me great pleasure to devote, say, one and a half million dollars for the erection of a suitable home for you all in New York City.

With best wishes,

Truly yours,

ANDREW CARNEGIE."

The land has been purchased in behalf of the societies, by Mr. Carnegie who has advanced $502,000 for the purpose, for which he is to be eventually reimbursed. The United Engineering Society, which is to hold the property, has been provided for under the laws of New York State, each of the three engineering societies named in Mr. Carnegie's letter being represented upon its board of trustees.

An architectural competition has been arranged in which six architectural firms have entered, and designs are to be submitted to the joint committee on June 20th, 1904. It is expected that the demolition of the buildings on the property will begin July 1st, 1904, and that this, and the construction of the new building will proceed continuously thereafter.

Building Fund Committee.—Four announcements have been issued by this committee, which reports that $41,000 has been pledged toward the amount of $200,000, the estimated requirement for the purchase of land, upon which Mr. Andrew Carnegie will erect the Union Engineering Building. The committee has received cordial and enthusiastic letters from Branches indicating that a strong regard for the Institute has been developed, which should encourage a liberal policy toward them on the part of the Institute as a whole.

Transmission Committee.—During the past year this committee arranged for papers and discussions at one day's session of the Convention at Niagara Falls, and a meeting in New York March 25. It is now making preparations for a special meeting at Chicago June 21 and 22, 1904, to be devoted exclusively to transmission subjects. A report of the committee at this meeting will embody the returns received from

the list of questions distributed last year. The success attained in gathering information in this field has led to a suggested plan by the chairman, that similar committees composed of engineers of experience, in the more important branches of electrical work, could by a systematic campaign take up the discussion of important problems at certain meetings of the Institute.

Engineering Data.—The chairman of this committee has made an earnest effort to gather information which could be utilized for the benefit of the membership. Nothing could be accomplished without co-operation, and having received practically no support, no progress has been made.

By-Laws.—During the past two years a committee has been engaged in framing by-laws, in order that the business and professional affairs of the Institute might be systematized. At the meeting of the Board of Directors, April 22, the by-laws reported by this committee were adopted, and are now in force. They have been printed in the April issue of the Transactions, and will subsequently be issued separately or in conjunction with the Constitution. If the membership will consult these by-laws the Secretary's office should be relieved of much correspondence, as many inquiries regarding the administration of Institute affairs will then be unnecessary.

Membership.—The total membership at the close of last year's report was 2,229, classified as follows:

Honorary Members	2
Members	417
Associates	1,810
Total May 1, 1903	2,229
Elected prior to May 1, 1903, and since qualified	177
Elected May 1, 1903, to April 30, 1904, and qualified	729
Restored to Membership	1
	3,136
Total Deaths	13
Total Resignations	12
Dropped as delinquents	84
	109
Grand total, April 30, 1904	3,027

The membership April 30, 1903, was classified as follows:

Honorary Members	2
Members	459
Associates	2,566
Total	3,027

The gain in membership during the year was 798, an increase of 35 per cent. As there are now applications pending and associates elected but not yet qualified to the number of 165, there is an immediate prospective total of about 3,300 members.

Associates Elected.—The Associates elected during the year, May 1, 1903, to April 30, 1904, and their present status is as follows:

Qualified and now Associates	729
Elections cancelled	1
Not qualified on April 30	89
Total elections	819

Resignations.—The following Members and Associates have resigned in good standing during the year:

Members.—Clayton C. Hall.

Associates.—W. J. Morrison, Jr., H. N. Ramsay, C. H. Thordarson, V. H. Yarnall, F. A. Cosby, T. H. Foote, F. J. Lamb, L. A. Lindsey, C. J. Marsh, J. C. Finney, Henry Schroeder.

Deaths.—There have been the following deaths during the year:

Members.—Frankland Jannus, T. E. Theberath.

Associates.—E. T. Gilliland, Benjamin Brown, J. J. Crawshaw, C. D. Crandall, W. O. Garrison, Francis Forbes, G. S. Johnson, J. L. Kebler, J. B. O'Hara, W. H. Simpson, F. E. Perry.

FINANCIAL STATEMENT FOR APRIL 30, 1904

ASSETS AND LIABILITIES.

Assets			Liabilities		
1903.		1904.	1903.		1904.
$2,006.75	Cash	$21,144.47	$787.93	General Library Fund	$369.67
	U. S. Bonds, market		4,643.60	Carnegie Fund	4,432.38
16,285.00	value	8,875.63		Land, Building and	
	Library Volumes and		1,100.00	End. Fund	7,609.93
9,436.75	Fixtures	21,737.13		Life Membership	
2,957.50	Transactions	4,624.50	4,200.00	Fund	4,400.00
	Office Furniture and			Mailloux Fund	1,000.30
495.30	Fittings	632.63	10,556.68	Reserve Fund (Cash)	12,3[illegible].07
154.50	Badges	138.00	19,311.48	Surplus(Property etc	)37,5[illegible].43
231.25	Congress Books	201.00			
8,407.64	Accounts Receivable	9,893.42			
500.00	Sec'y's petty cash	500.00			
125.00	Type, etc				
$40,599.69		$67,746.78	$40,599.69		$67,746.78

RECEIPTS AND DISBURSEMENTS.

Ordinary Receipts.			Ordinary Disbursements.		
1903.		1904.	1903.		1904.
$3,305.00	Entrance Fees	$4,463.00		Stenography & Type	
17,583.95	Current Dues	25,219.50	$697.00	writing	$547.44
1,168.47	Past Dues	1,523.12		Stationery & Print-	
740.59	Advance Dues	1,025.50	2,148.15	ing	3,058.36
◆ 600.00	Life Membership Fee	◆ 200.00	1,543.50	Postage	1,947.52
1,752.24	Transactions Sales	1,249.83	346.54	Express	813.83
463.63	Transactions Subs	543.40	619.93	Badges	1,059.74
64.63	Binding	49.35	667.95	General Expenses	742.96
1,685.51	Advertising	3,185.87	93.00	Certificates	36.50
23.67	Electros and Cuts	23.79	239.60	Office Furniture	359.72
783.50	Badges	1,164.50	5,350.41	Salaries	6,027.88
220.00	Transfer Fees	493.00	1,778.93	Cuts and Electros	1,909.67
16.10	Congress Books	9.00		Publishing Transac-	
496.36	Interest	544.13	7,254.16	tions	9,067.47
	Students' Dues	1,203.00	1,588.04	Rent	2,370.04
	Exchange	12.79	804.88	Advertising Com's'ns	232.50
	Branch Meetings	77.00	577.71	Binding Volumes	576.18
1,028.23	Library Donations			Binding Pamphlets	876.83
242.80	Library Volumes		1,208 43	Meeting Expenses	772.55
5.00	Meeting Refund		40.65	Branch Meetings	1,184.34
1.57	Postage		154.27	Office Expenses	107.58
				Library Rent	1,505.04
			3,994.62	Library Salaries	828.00
				Library Miscel	393.21
				Library Volumes &	
			330.00	Fixtures	1,417.97
			21.00	Students' Expenses	17.25
				Expenses Land, Bld.	
				& Endowment Fd.	
◆ 621.58				Balance	◆ 4,592.58
$30,181.25		$40,986.78	$30,181.25		$40,986.78

SPECIAL RECEIPTS AND DONATIONS AND SPECIAL EXPENDITURES

(Not Embraced in Above Statement.)

Special Receipts and Donations. 1904.		Special Expenditures. 1904.	
Land Building and Endowment Fund, Donations	$6,509.93	General Library Fund, Expenditures	$53.37
General Library Fund, Donations	208.05	Mailloux Special Fund	29.20
Mailloux Fund, Donation	1,000.00	Carnegie Fund, Disbursements by Warrant	492.39
Mailloux Fund, Interest	29.50	Carnegie Fund, Disbursements from Petty Cash	36.75
Sale of U. S. Bonds	7,409.37	Balance	14,545.14
Total	$15,156.85		$15,156.85

The total receipts for 1904, exclusive of donations, were in excess of 1903	$11,833.76	
The total Disbursements for the year 1904 were in excess of 1903	6,834.53	
Due from Members account of entrance fees and dues	9,281.78	
Due on Miscellaneous accounts	611.64	
Unpaid bills, May 1, 1904, amount to	246.44	
Total Cash Receipts from ordinary sources	40,986.78	
Total Cash Disbursements, account ordinary expenses	36,394.20	
		$4,592.58 ◆
Property on hand according to inventory, May 1, 1904:		
Office Furniture and Fittings	$632.63	
Badges	138.00	
Transactions	4,624.50	
Congress Books	201.00	
Library, Volumes and Fixtures	21,737.13	
		$27,333.26
TOTAL NET ASSETS.		
Cash:—		
Mercantile Trust Co., deposit	$7,861.44	
Farmers Loan & Trust Co., Gen'l Library Fund	369.67	
Farmers Loan & Trust Co., Building Fund	7,609.93	
Farmers Loan & Trust Co., Carnegie Fund	4,303.43	
Certificate of Deposit, Mailloux Fund	1,000.00	
	$21,144.47	
Secretary's Petty Cash	500.00	
U. S. Bonds, market value	8,875.63	
Inventory (as above)	27,333.26	
		$57,853.36
Total Net Assets last year		32,192.05
Increase		$25,661.31

PROPERTY PURCHASED DURING THE YEAR.

(Reported as directed by the Constitution.)

Office Furniture and Fixtures	$359.72
Library Fixtures	370.00
Library Books and Binding	1,047.97
Transactions	1,747.50
	$3,525.19

Respectfully submitted for the Board of Directors,

RALPH W. POPE,

Secretary.

◆See explanation regarding comparative balances, third paragraph in text under head of Finances.

TREASURER'S REPORT.

FROM APRIL 30, 1903, TO MAY 1, 1904.

Dr.

Balance from May 1, 1903		$2,006.75
Received from Secretary, May 1, 1903, to May 1, 1904,		
on account of General Fund		42,314.84
on account of Carnegie Fund		4,795.82
on account of Library Fund		423.04
on account of L. B. and Endowment Fund		7,609.93
on account of Mailloux Fund		1,000.00
		$58,150.38

Cr.

Disbursements on warrants from Secretary, Nos. 1833 to 2143, inclusive			
	against General Fund		$36,460.15
Warrants No. 1 to 14 Inclusive	against Carnegie Fund		492.39
	against Library Fund		53.37
Balances to New Acct. General Fund		$7,861.44	
"	Carnegie Fund	4,303.43	
"	Library Fund	369.67	
"	L. B. & End. Fund	7,609.93	
"	Mailloux Fund	1,000.00	
			$21,144.47
			$58,150.38

Respectfully submitted,

GEORGE A. HAMILTON,

Treasurer

REPORT OF COMMITTEE ON LOCAL ORGANIZATIONS.

To the Board of Directors of the American Institute of Electrical Engineers:

At its September meeting in 1902 the Board of Directors appointed a Committee on Local Organizations for promoting the organization of local meetings. The primary purpose of these meetings was stated to be the presentation of the papers and discussions of the regular meetings of the Institute and for the discussions of them, to be supplemented, however, by new papers, especially on subjects of local interest. The Committee was further given the general direction of a new line of work in connection with technical schools and universities by which local Institute meetings should be held among the students.

The present system of local meetings has been organized under the general auspices of the Committee; the local organizations, however, have been comparatively free to adopt such methods as seemed best. In the light of the experience thus gained the Board of Directors has recently adopted by-laws relating to the organizations and conduct of local meetings. Local meetings are now organized in 29 places which include many of our principal cities and technical schools. Branches are formed in each of the four cities ranking next to New York in population.

Statistics.

The accompanying statistics have been prepared from the monthly reports and other data in the Secretary's Office, checked in most cases by the local secretaries.

Several striking features in connection with the statistics are the following:

1. *Attendance.*—The monthly aggregate attendance at the Branch meetings is over 1300; the average attendance at the New York meetings does not exceed 200. It follows therefore that the number of men who come in personal contact with the Institute through Branch meetings is six times as great as through the New York meetings.

Discarding the meetings in technical schools the aggregate membership in 10 cities in which branch meetings are held is 888 and the aggregate average attendance at these meetings is 729. The attendance including visitors is 83% of this membership. The Institute membership within commuting distance of New York is 794 and the attendance at the New York meetings is, say 200, or 25% of this membership. It follows therefore that the attendance at the branches is proportionately greater than that at the general meetings in New York City.

STATISTICS OF BRANCHES, MAY, 1904.

	Branches and Date Started.	Jun. 1 1902.	Membership Apr. 20 1904.	Increase	A.I.E.E. Students	Meetings Since Oct. 1902	Average Attendance.	Original Papers Since Oct. '02
1	Chicago. 1893	76	152	76	39	12	115	6
2	Minnesota. Apr. 7, '02	9	12	3	5	16	20	1
3	Pittsburg. Oct. 13, '02	44	128	84	15	17	113	6
4	Cornell University. Oct. 15 '02	5	14	9	19	20	58	2
5	Lehigh Universit . Oct. 15, '02	3	4	1	1	15	35	3
6	Univ. of Wisconsin Oct. 15, '02	6	19	13	12	66	25	2
7	Univ. of Illinois. Nov. 25, '02	2	5	3	6	12	45	0
8	Denver. Dec. 8, '02	6	32	26	—	6	40	4
9	Cincinnati. Dec. 17, '02	15	47	32	2	8	55	3
10	Ohio State Univ. . Dec. 20, '02	2	2	0	13	17	28	1
11	Penna.StateCollege Dec. 20, '02	1	1	0	11	38	32	2
12	Univ. of Missouri.. Jan. 10, '03	1	1	0	5	12	22	0
13	St. Louis. Jan. 14, '03	14	60	46	—	13	24	4
14	Purdue University. Jan. 26, '03	5	5	0	48	14	24	2
15	Schenectady. Jan. 26, '03	49	113	64	17	11	110	3
16	Philadelphia. Feb. 18, '03	55	92	37	1	13	98	6
17	Boston. Feb. 13, '03	120	195	70	2	10	127	7
18	Iowa State College. Apr. 15, '03	1	5	4	21	14	58	8
19	Washington, D. C. Apr. 9, '03	28	44	16	1	10	58	13
20	Toronto. Sept. 30, '03	4	24	20	4	7	15	2
21	Columbus. Dec. 20, '03	4	33	29	1	8	14	1
22	Seattle. Jan. 19, '04	11	17	6	—	3	15	—
23	Atlanta. Jan. 19, '04	4	19	15	5	1	8	—
24	Armour Institute.. Feb. 26, '04	1	1	—	31	3	25	2
25	Washington Univ. Feb. 26, '04	1	1	—	6	1	5	—
26	Univ. of Michigan. Mar. 25, '04	3	3	0	17	1	25	—
27	Univ. of Arkansas. Mar. 25, '04	1	2	1	2	4	22	1
28	Worcester Polytechnic Institute. Mar. 25, '04	5	10	5	4	21	35	1
29	Pittsfield. Mar. 25, '04	13	27	14	—	2	65	—
		494	1068	574	273	375	1316	80

Again, the total attendance at the New York meetings is equal to 6 per cent. of our membership while the total attendance at the New York and the Branch meetings is nearly 50% of our membership.

It may be noted that the attendance at branch meetings includes a much larger proportion of non-members than the New York meetings. This indicates a wider influence through the branch meetings than there is in New York. The room in which the New York meetings have been held has been too small to accommodate those who would be glad to

attend so that the invitations to outsiders have been restricted. This limitation may be removed when the new Engineering Building is completed.

2.—*Branches in Cities.*—The successful organization of branches in the larger and older cities which are already supplied with engineering societies and technical meetings is notable. Some of the strongest and best supported of the branches are in such cities. Electrical workers distributed through manufacturing and operating companies and other interests in these cities have not been brought together through engineering societies, nor has the INSTITUTE itself appealed to many of them. The INSTITUTE meeting has a distinct value from the engineering standpoint and the advantage of acquaintance and association, and has in fact opened a new field which has not been clearly recognized. Branches have been formed in fifteen cities.

3. *Student Meetings.*—The general interest taken in INSTITUTE meetings by students is significant. Professors of electrical engineering recognize the value to their students of the work of the INSTITUTE and a study of its papers reflecting as they do the present tendencies of electrical engineering and the latest achievement in electrical work. In some institutions electrical engineering societies which were languishing have taken on new life as in INSTITUTE branches. Meetings are held in fourteen institutions. The average attendance is over 400. This attendance of students does not include those who attend the Branch meetings in cities.

4. *Papers and Discussions.*—The Branch meetings are supplied with the papers presented at the New York meeting and the stenographer's report of the discussion upon them. The discussion at the Branch meeting is not infrequently by members who are better qualified to discuss the subjects in hand than those in attendance at New York. The Branches contribute materially to the value of our transactions, both by the discussion of papers and by the occasional presentation of new material.

BRANCH REPORTS.

As a basis for the preparation of this report a circular letter was sent to the officers of the several branches from which the following is an extract:

"In addition to statistics showing the number of branches, membership and the like, it is desired to indicate the ways in which the work done in branches and in Student meetings is contributing to the welfare of the INSTITUTE and of its members, both collectively and individually.

"The rapid development of local organizations during the past year and a half has been one of the most notable features of our INSTITUTE activity. What results are being accomplished? What changes are being effected in the scope and effectiveness of our work? Is the local meeting simply an affair of passing interest, based on the enthusiasm of the moment, or has it a substantial basis? What do the conditions which are found and the results already attained indicate as to the permanency and the ultimate scope and value of this work?

"It is desired to have from those intimately identified with the work

of the branches, statements or reports upon which a general report may be based which will give a fair estimate of the success of this movement to broaden and nationalize the active work of the INSTITUTE.

" I would be pleased to have a letter from you giving your observations and views. It is suggested that the branch work be considered from the following points of view: [The six headings are given later in connection with the reports]."

Replies were received from all but two or three of the branches. In many cases both Chairman and Secretary replied and in Boston and St. Louis the letter of inquiry was transmitted to several members and a number of independent views were obtained. In all reports have come from 45 members of 27 of the 29 local centers. The mere fact that so many men—most of them busy men—have taken this interest in the matter is significant.

The striking feature in the reports is the unanimity of sentiment. There are none that do not show satisfaction with the results in the past or confidence in the future. Some propose new methods, but none even suggest discontinuing their work.

It is no easy matter to bring into brief compass the contents of so many reports. A general summary will be given and extracts will be made from some of the letters, although much that is intrinsically worthy cannot be given in the space available.

---

1. *The value of the Institute to its members as affected by Branch meetings.*

The replies are unanimous that the INSTITUTE is of much greater usefulness to its members. Following are some of the expressions:

" Until the establishment of the Branches the value of the INSTITUTE to its members outside of New York, was largely of a sentimental nature." (Sanville, Philadelphia.)

" Hence from the educational view point I would conclude that the benefits derived from the local meetings are equal, if not superior to those derived from the regular meetings. In addition to the educational factor, there is the social element which constitutes a feature no less valuable than the educational one just referred to." (Freeman, Chicago.)

" Branch meetings give members something tangible in return for their money. We get as much benefit from the INSTITUTE as those members who live near New York City." (Humphrey, St. Louis.)

" I find that our meetings have quickened my interest and forced me to go thoroughly into each paper." (Shaw, University of Missouri.)

" The advantages gained both by the members and the INSTITUTE fully justify maintaining and continuing the branches." (Ayer, Boston.)

" The Branch meetings increase the value of the INSTITUTE to members of the local branch at least 100%." (Damon, Chicago.)

" The Branch meetings have more than doubled the value of the INSTITUTE to the local members." (Lanphear, Iowa State College.)

---

2. *The effect of Branch meetings on the attitude of members toward the Institute.*

The replies show that there is closer personal interest and wider activity.

"Members feel now that they have a direct personal interest in all that the INSTITUTE does." (Humphrey, St. Louis.)

"The Branch meetings are of value in giving a personal element that is altogether lacking when membership means only paying dues and receiving the printed transactions." (Langsdorf, Washington University.)

"Personally I am of the opinion that the organization of the Boston Branch has prevented the Boston members from losing interest in the INSTITUTE. At various times during the past five years I have made efforts to get friends of mine in Boston to join the INSTITUTE but have always been met with a very decided feeling that it was not worth while; that the INSTITUTE was operated as a New York Club and was of no possible interest to any one outside of that city. How much truth there has been in this I cannot say but the starting of the Branch last year revived interest very decidedly and I think it has been a wonderful success." (Edgar, Boston.)

"The Branch meetings in the western towns serve to bring the members in closer touch with the INSTITUTE for the reason that very few are ever able to attend the New York meetings or the conventions." (Shaad, University of Wisconsin.)

"The Branch makes it possible to give a large number of men actual work to do for the INSTITUTE, which always results in a feeling of closer relationship than the occasional attendance at a meeting in New York gives. We accomplish this in Philadelphia by forming special committees and distributing the Branch work as widely as possible." (Sanville, Philadelphia.)

"A number of members who formerly took comparatively little interest in the affairs of the INSTITUTE are taking an active interest in the Branch meetings." (Eglin, Philadelphia.)

---

3. *The effect of Branch meetings upon the attitude of non-members, particularly young men, to the Institute.*

The general tenor of the replies is indicated by the following extracts from the reports received:

"The attitude of non-members particularly young men to the INSTITUTE has been shown by the large influx of such men to the ranks of the INSTITUTE." (Bogen, Cincinnati.)

"The standing of the INSTITUTE locally is considerably increased. This was seen in our meeting last year when Mr. Arnold read a paper on, 'The Transportation Facilities of Chicago,' and when we had several members of the City Council with us who entered into the discussion." (Swope, St. Louis.)

"I certainly would never have joined the INSTITUTE had not this Branch been formed." (Caldwell, Boston.)

"I am satisfied that practically all of the members that have joined since we started the Branch meetings, have done so as a result of their interest in these meetings." (Hewitt, Philadelphia.)

"The Branches have a tendency to bring into the INSTITUTE a larger number of men, who have no professional standing, than would otherwise have come in. These men, however, are frequently the men who are doing the actual, new engineering work for the various corporations and industries. They are therefore a valuable acquisition to the INSTITUTE." (Sanville, Philadelphia.)

"Fully two-thirds of the attendance at our local meetings has been young men who have not yet become members of the INSTITUTE. It is

hard to say how any better plan than that of local meetings could be adopted to educate future members to the possibilities of the INSTITUTE work." (Damon, Chicago.)

"The conditions with the Pittsburg Branch are somewhat unique in that it meets in the hall of the Electric Club and is affiliated with the Electric Club [composed of engineers and apprentices of the Westinghouse Electric & Mfg. Company] to the extent that all of its members are invited to participate in the meetings. This circumstance perhaps gives the local branch an unusual opportunity for interesting those who are very apt to take advantage of membership in the AMERICAN INSTITUTE, and probably accounts to some extent at least, for the rapid growth of local membership which has nearly tripled in less than two years." (Lincoln and Peck, Pittsburg.)

---

4. *The value of Institute work to students.*

In some cities students attend the local branch meetings. (Student meetings in technical schools will be considered later.) In Chicago, St. Louis and Columbus meetings have been held both by the branch and by the Students in technical schools.

The relation of some of the Branches in cities to students is indicated by the following extracts:

"We not only have got a lot of new members, but what is still better we have interested all the electrical students of this section of the country in the INSTITUTE, so that the majority of them, I think, rather look forward to joining when they get out of college." (Edgar, Boston.)

"Branch meetings must be of especial benefit to younger members, and that these young men take a deep interest in the meetings, I can vouch for, as a number from these works attend every one of our meetings in Boston. There have also been enroled thirty-six young men in the grade of Student. I am not familiar with the work of the college branches, but the interest taken by the students—so-called—of the General Electric Company [Lynn Works] indicates that the general interest of these young men is more than superficial." (Fleming, Boston.)

"The local meetings have been of great help to those who have attended. Our senior electrical engineering students attend the meetings almost to a man." (Shepardson, University of Minnesota.)

---

5. *Do the Branches aid the Institute in its fundamental purpose,—"in the advancement of the theory and practice of Electrical Engineering * * * and the maintenance of a high professional standing among its members."*

The general tenor of the reports is to the effect that the Branches conduce to the substantial advancement of Electrical Engineering. In other words, the meetings do more than simply impart information and contribute to agreeable friendships. A few of the expressions are as follows:

The substantial advancement of the INSTITUTE is effected through Branch meetings "(a) by greatly increasing the number who come under the influence of the INSTITUTE;

"(b) by bringing to a much larger audience the papers presented;

"(c) By making a much larger number acquainted with the work and personality of the greatest engineers of the country;

"(d) By bringing out material for papers that would not otherwise be presented." (Caldwell, Columbus.)

"The Toronto Branch has aided in the advancement of the theory and practice of electrical engineering by the discussion which takes place

and which soon indicates who have the highest attainments, and in consequence a professional pride is developed which would not pe present were it not for the meetings of the Branch of the INSTITUTE." (Kammerer, Toronto.)

" The Branch is undoubtedly aiding in the proper preparation of men for the profession, and as a result it must in a secondary way be tending toward the future advancement of the profession." (Jackson, Pennsylvania State College.)

" The bringing about, rather than ' the maintenance of a high professional standing among its members ' will naturally take place by bringing the young men into personal relation with the full members, providing always that the qualifications for entrance to the higher ranks are made high." (Bogen, Cincinnati.)

" It is believed that the influence of this Branch will be felt over a large part of the Southeastern States and will tend to place the ethics of the profession on a higher plane." (Shoen, Atlanta.)

6.—*Is there a sustained interest in Branch meetings?*

It was anticipated that many branches would spring up in which interest would wane when the initial enthusiasm had spent itself. Local meetings have organized in 30 places. There has been but one suspension, that being in connection with a minor college in which there was a change of professors. Of the 29 remaining, one is in a state of suspended animation (a number of the leaders have left the city), but the others seem to be in a healthy condition. It is gratifying to note in reviewing the reports, the practically universal assurance that there is a sustained interest and that the prospects for the future are encouraging. A number of the branches have been started recently so that there is little experience upon which to base conclusions. There is a suggestion in the reports from two of the larger cities, in which there appear to be strong local engineering societies, namely Chicago and St. Louis, to the effect that it may not be best to hold meetings as frequently as once a month. A few of the reports, principally from the older branches are as follows:

" There is certainly a sustained interest in the branch." (Burch, Minneapolis.)

" There is a pronounced interest in our local branch. The prospects for the future are very bright. We have a constantly growing membership among a good class of men." (MacKeen, Toronto.)

" The interest in the branch meetings has increased since its organization and the future prospects are bright." (Eglin, Philadelphia.)

" With regard to the St. Louis Branch I fear that it will be difficult to maintain interest under present conditions. Two meetings per month of the Engineers' Club, with one of the INSTITUTE, is too much of a drain on one's time for regular attendance at all of them. We should, I think push the matter of arranging a compromise system with the Engineers' Club, as outlined over a year ago." (Langsdorf, St. Louis. Layman expresses a like view.)

" There continues to be much interest in the Boston Branch and its prospects for the future are good." (Kennelly, Boston.)

" There is every indication that we shall not only maintain this interest, but increase the membership in this locality." (Bogen, Cincinnati.)

"We are glad to say that the interest in the meetings is well sustained and the prospects for the future are bright. In order to keep up a general interest we have had to introduce new subjects and we feel that our proceedings in this respect is accountable for the sustained interest in the meetings." (Betts, Washington, D. C.)

"I think we can safely say there is a substantial interest in the Chicago Branch and I further believe that its prospects for the future are very good." (Junkersfield, Chicago.)

STUDENT MEETINGS.

The introduction of INSTITUTE meetings in technical schools has brought results which are remarkable and significant. The instructors have taken up the matter with much interest and the students have taken hold in a substantial and enthusiastic way.

The manner of organizing and of conducting the meetings differs in different institutions. At one extreme the study of the INSTITUTE papers is taken up in a Seminary method under the direction of the professor as a part of the regular course. Weekly meetings are held and credit is given. On the other hand, an electrical engineering society among the students has merged into an INSTITUTE meeting with suitable by-laws and officers. Between these extremes various methods are pursued as may be best adapted to the local conditions. In general, however, the methods are the same in that the current INSTITUTE papers with their discussions are presented by students to whom they have been assigned. The subjects are then open for further comment and discussion. Current papers are often supplemented by past papers; the transactions of the INSTITUTE being in fact one of the best libraries of electrical engineering information.

The reports from the Student meetings are practically unanimous in showing active interest and substantial results. It is impracticable to give in full the reports received. The few extracts which are given, however, will serve to cover the ground and several are given rather fully to indicate typical methods by which the work is conducted.

"My opinion of the value of the INSTITUTE work has grown steadily as I have had a chance to observe its effects on students and graduates. They have grown under it and take a larger, broader view of the profession. They take pride in it. It calls for the exercise of sound judgment, and, as it were, stretches their minds to consider the larger problems of strictly engineering character. They are unanimous in their appreciation of the privileges they enjoy.

"Prospects for the future are bright. I expect to have a meeting a week during the next school year." (Shaw, University of Missouri.)

"A certain number of the senior class, together with the graduate students in Electrical Engineering, elect our course known as a Graduate Conference or Seminary and such students are invited to become affiliated with the INSTITUTE as Student Members or to join as associates, though this is not made a requirement of the course.

"Meetings of this Seminary are held weekly and different subjects are taken up and discussed, such subjects being furnished largely by papers presented at previous meetings of the INSTITUTE. A list of other references is prepared by the student who is to abstract the paper and the references. A written discussion to serve as the opening of a general discussion is required from a different student.

"One meeting of each month serves as the regular meeting of the Madison Branch. These monthly sessions are held at private houses mostly, and are open to any person who may be interested. These meet-

ings have been very successful this year. They are very informal, much in the nature of a "smoker," and have been well attended." (Shaad, University of Wisconsin.)

"I believe that a very decided reaction upon the work in the Department is felt in that in certain directions a practical turn is given to our Instruction work and in this way the local branch meetings are aiding in the advancement of the theory and practice of Electrical Engineering. The interest in the local Branch is sustained and increasing. We have recently sent in over thirty applications for Student membership and some additional applications for Associate membership, in the parent society." (Spinney, Iowa State College.)

"Four men who became Associates while here have left Ames which accounts for their not appearing in the list of local membership. During the past month four other men have made application. These applications are a direct result of the influence of the local branch." (Lanphear, Iowa State College.)

"This Branch consists of some thirty-one student members who are actively interested in the work of their branch, and at the same time are frequent visitors to the Chicago Branch meetings, as well as the local branch of the Western Society of this city. These young men discuss papers of their own that are the result of their experiences in the class room and the laboratory, as well as those of the INSTITUTE that come within their range." (Freeman, Armour Inst. of Technology.)

"The local branch is causing our students to become thoroughly acquainted with the INSTITUTE and to hold its aims and objects in high regard. This attitude is not confined merely to the local student membership but is true of the entire two hundred odd students pursuing Electrical Engineering." (Jackson, Pennsylvania State College.)

"During the past ten years there has existed among our students a vigorous organization known as the Cornell Electrical Society. This Society holds usually about 15 meetings a year for the purpose of hearing lectures or engaging in discussions. * * * This is one great reason why we have in the past held most of our branch meetings at an hour that would otherwise be given up to regularly required work for our seniors in Electrical Engineering. Another reason for doing this is that we want to require that every one of our electrical engineering graduates shall possess knowledge of the INSTITUTE, the benefits to be derived therefrom to have a start in the study and understanding of the transactions, and finally to know something of the men who have been or who are now prominent in its management or in the contribution to its transactions. We have remodeled the schedule of our senior courses somewhat for the express purpose of devoting one hour of required work per week to the INSTITUTE and its transactions." (Ryan, Cornell.)

"The work of the organization at this place has exceeded my expectations.

"The weakness of the isolated student organization which existed before the Branch was installed, was that it relied almost wholly upon local talent for the papers; the students themselves taking little or no part in the discussion of the same. Most of the work devolved upon the members of the engineering faculty.

"It has been our policy to leave the work of the Branch largely in the hands of the students, we acting only in an advisory capacity and the results have been very gratifying.

"The increased number of calls for the transactions of the INSTITUTE in our library shows that the students have learned to appreciate the proceedings of the INSTITUTE as a source of reliable information". (Esterline, Purdue.)

"The students learn to know the leaders in INSTITUTE discussions, learn what are vital topics, and in general to believe that electrical engineering is something more than a matter of text-book knowledge. The

students appreciate the opportunity, and many have told me they would join as soon as able to pay the fees. The western state university is filled with a lot of eager but impecunious students, who are often actually unable to pay $3 for student membership, on account of class assessments, especially in their senior year.

"At the moment, judging from our experience I should say that the INSTITUTE is giving more than it is receiving, doing a glorious work. If the Branch privileges were removed I am sure we would feel the loss severely.

"The interest is sustained. We would like to get more advance papers, owing to our increased attendance, but I am ashamed to ask for them, unless the INSTITUTE makes arrangements to have at least the postage refunded." (Brooks, University of Illinois.)

"After the organization of the St. Louis Branch I encouraged my students to enroll as Student Members and to attend the regular monthly meetings. The response, however, was not encouraging, and inquiry developed the fact that the discussions were often too far in advance of the instruction (at the time of the meeting) to be intelligible to the students. For this reason it was decided to form an independent branch, so that discussions might be more free; incidentally, this permitted the reading and discussion of earlier INSTITUTE papers bearing on the subject studied in the class-room, in case the current ones should be ahead of the schedule of studies." (Langsdorf, Washington University.)

"Our first meeting was attended by some 65 students and visitors. Our branch is, I believe, a permanent organization in the University." (Gladson, University of Arkansas.)

"The prospects for next year seem very promising, the men being interested in the work of the branch, and anxious to see it succeed." (Sargent, Worcester Polytechnic Institute.)

BY-LAWS.

The By-Laws which have been recently adopted by the Board of Directors regarding branches formulate the general policy under which branches have been conducted during the past year and a half. There is a definite general relationship with the INSTITUTE and the important matters pertaining to the branch are subject to the approval of the Board of Directors. The branch, however, is allowed a wide latitude in the adoption of its methods and its rules and regulations. Conditions vary in different places and the branch is permitted to adopt methods which are best suited to the local requirements.

In the By-Laws a distinction is drawn between Branches (which require at least ten Members or Associates) and Student meetings. The Student meeting is responsible to the INSTITUTE through one of the members of the INSTITUTE who is a professor in the technical school. He is at liberty to follow such plans as may be found best. In those institutions in which there are ten or more Students of the INSTITUTE the Student meetings may be termed Branches. The organization, however, is virtually a meeting held under the direction of the professor in so far as official relations with the INSTITUTE are concerned, unless there be ten Members or Associates, in which case a Branch may be formed.

The privileges and the status of Students of the INSTITUTE are set forth in the By-Laws and it is expected that there will be a material increase in the number of Students during the coming year.

AFFILIATION WITH LOCAL SOCIETIES.

In several instances it has been found convenient or expedient to have the branch work in close relations with a local engineers' club or engineer-

ing society. Relations of this kind have been fostered. It has been the general policy to minimize the organization and management of the branch and to have it primarily devoted to meetings for the reading and discussion of papers. A preferred arrangement is that in which a local society will extend the use of its assembly hall for the INSTITUTE meeting, there being a general privilege and invitation to the members of the local society to attend and take part in the meetings. In this manner the benefit has been mutual. The INSTITUTE meeting may be regarded in one sense as a section meeting of the local society. On the other hand, the branch preserves its identity and there is no interference with the individualities of the two organizations.

GENERAL CONCLUSIONS.

The new place in modern affairs which has been taken by engineering, the great developments which have come through the application of electricity, the growth of the A. I. E. E. from its organization 20 years ago this month to the position which it now holds; the development of a new profession, the importance of the responsibilities devolving upon it—all open a new field for national engineering societies and for our INSTITUTE. The field and the requirements in engineering are different from those of 25 years ago. The field and the requirements in our own INSTITUTE are different from those of ten or even five years ago.

In most professions a man who was a competent engineer ten years ago might take up work now even though he had been out of touch with his profession in the meantime, but an electrical engineer who has not kept abreast of the changes in the past ten years would be quite out of date. The majority of the men in the profession are young men and hundreds of others are coming from the technical schools each year.

"It is the function of the AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS to bring individual workers into a common unity, to join them in a community of interest—a fraternity which is called the electrical engineering profession.

"It is the function of the INSTITUTE to bring together continually the diversified achievements of many workers which taken altogether constitute a single total of accomplishments—a total which is called progress." (President's address, October, 1902.)

In meeting these new demands and fulfilling the new conditions there must be a broadening of our activities. One of the most effective ways of nationalizing our INSTITUTE and of increasing its effectiveness is through the local organization. The Electrical Engineering profession therefore presents to our INSTITUTE a field for Branch meetings which is unique, and which is quite different from that possessed by our sister societies. We are confronted by new conditions; we must devise new methods. The results so far achieved and the indications now presented justify the belief that the formation of our branches is not merely a matter of present enthusiasm but that a new department of our work is begun which promises to be permanent and far-reaching in its influence.

For the Committee on Local Organization,

CHAS. F. SCOTT,
Chairman.

BLANK
PAGE

REPORT OF COMMITTEE ON THE CADMIUM CELL.

To the Board of Directors of the American Institute of Electrical Engineers:

The committee appointed by you to report on the preparation of materials and the construction of the cadmium or Weston cell has made very substantial progress, and begs leave to make the following preliminary report, with the request that the Committee be continued.

The most serious variations in the electromotive force of both Clark and Weston standard cells have been traced to the influence of the mercurous sulphate. (See Zeitschrift für Instrumentenkunde, February, 1901, and the Report of the National Physical Laboratory of England, for 1903.) The problem of ascertaining the cause of these variations and the development of a standard method of preparing the mercurous sulphate was accordingly taken up by the Chairman of this Committee in conjunction with Dr. George A. Hulett of the department of chemistry in the University of Michigan.

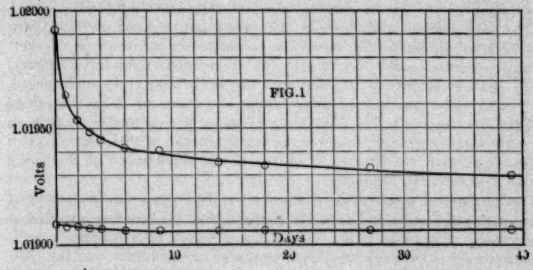
The method of preparation in use by the European manufacturers of mercurous sulphate consists in its precipitation by bringing together a solution of mercurous nitrate and sodium sulphate or sulphuric acid. This method has been repeated with a number of variations; and the various preparations give variable results when used in the cadmium cell, and all of them higher electromotive force than the mercurous sulphate prepared electrolytically, as described below. These results suggest that perhaps mercurous sulphate might carry isomorphously a small quantity of mercurous nitrate, since both of these salts crystallize in the monoclinic system. In fact Dr. Hulett has detected the nitrate in commercial preparations and in some of those made by himself. A cell set up with mercurous sulphate of the standard preparation, to which a trace of mercurous nitrate had been added, showed an increased electromotive force due to the nitrate. Not only does the presence of the nitrate raise the electromotive force of the cell, but the relative amount of the nitrate present appears not to be invariable.

In view of these facts, a new and standard method of making mercurous sulphate from pure mercury and dilute sulphuric acid appeared to be highly desirable. Such a method has been devised by Dr. Hulett; also independently by Dr. Wolff of the Bureau of Standards. (See paper by Henry S. Carhart and George A. Hulett in the Transactions of the American Electrochemical Society, Vol. V; also one by F. A. Wolff, same volume.)

A new electrolytic method of preparing the cadmium amalgam, and one for washing the mercurous sulphate to remove the acid without the use of pure water were also devised. (See specifications below.) The results are highly satisfactory, and cells made in accordance with the specifications appended to this report show remarkable agreement and constancy. Your Committee is well satisfied that the principal difficulties in making Weston cells have now been removed.

The two curves in Fig. 1 show the behavior of two cells for forty days after they were placed in a constant temperature bath, at 21.1° cent. Cell *D*6 was made with mercurous sulphate prepared in the old way by precipitation; cell *D*1 was made with the same materials, except that the electrolytic mercurous sulphate was used. Comment is unnecessary. The electromotive forces given are relative and not absolute.

The table exhibits measurements made on cells *D*1 to *D*4, and *F*1 to *F*10 all of them set up with the electrolytic mercurous sulphate. The figures were obtained by comparison with an old cell, *B*7, by means of a Wolff's potentiometer and a type *H* d'Arsonval galvanometer made by Leeds &



Northrup. The fifth decimal place could be read with the greatest ease.

In determining the effect produced by changing a single feature in the preparation of the materials, about 100 cells of the *H*-form have been made and tested. These are still under observation. All of them, except the first ten, have been hermetically sealed. The sealing is readily effected by making the glass containing cell of a special form, and sealing with two blast lamps.

The Committee offers the following Specifications, which are to be considered as provisional only, for the preparation of the cadmium cell with saturated solution and excess of crystals of cadmium sulphate. For the cell so prepared the Committee would suggest the name, "Weston Normal Cell."

1. Mercury.

Mercury free from grease should be first shaken with a nitric acid solution of mercurous nitrate,* and, after drying, it should be distilled in a vacuum at least twice.

*Zeit. Ph. Ch., 33, 611.

Date.	D CELLS.				Date.	F CELLS.									
	1	2	3	4		1	2	3	4	5	6	7	8	9	10
Jan. 5, 21.0°	1.01909	1.01910	1.01910	1.01910	Feb. 15, 21.1°	1.01907	1.01907	1.01907	1.01908	1.01908	1.019065	1.01907	1.01908	1.01905	1.01907
6, 21.1°	08	09	09	09	16, 21.1°	065	06	07	08	07	06	06	07	07	065
7, 21.1°	08	C8	085	09	17, 21.1°	07	07	07	07+	07	06	075	075	07	07
9, 21.1°	07	08	08	08	20, 21.1°	07	07+	075	08	08	08	075	07	08	075
11, 21.1°	07+	07	07	08	22, 21.2°	075	08	08	08	08	08	08	08—	08+	08
14, 21.1°	07	06	07	075	25, 21.0°	08	08	08	08	085	085	08	08	09	08
19, 21.1°	06	065	07	07+	Mar. 1, 21.1°	08	08	08	08+	08	08	08	08	08+	08
23, 21.1°	06	06	07	07	4, 21.2°	08	08+	08+	08+	08	08	08	08	08	08
Feb. 1, 21.1°	065	065	07	075	12, 21.0°	075	08	08	08+	08	08	08	075	08	08
13, 21.1°	07	08	08	085	15, 21.1°	08	085	09	09	08+	08	08	085	085	09
16, 21.1°	07	08	08	08	17, 21.3°	075	08	08	08	08	08	08	08	08	08
18, 21.1°	07	07	08	08+	21, 21.3°	07	07+	08	075	07+	07	07+	07+	08—	08
22, 21.2°	07	08+	09	09	23, 21.3°	07	075	08—	075	07	07—	07	075	08—	
25, 21.2°	07	08+	085	09	28, 21.0°	075	08	08	085	08	075	075	08	08	
Mar. 1, 21.1°	07	07	075	08	Apr. 2, 21.2°	07	07+	08	08	08	075	08	08	08+	
5, 21.2°	07	07	075	08	5, 21.1°	075	08	08	08	08	075	08	08	08	
12, 21.1°	07	07	07	07+	9, 21.0°	08	08	085	08	09	08	08+	08	08+	
15, 21.1°	C7	C7+	07	075	16, 21.0°	08	085	085	08+	085	07	08	08	085	
17, 21.0°	06	065	07	07+	28, 21.1°	07	075	08	08	08+	08	08	08	08	

2. Cadmium Sulphate Solution.

The best pure commercial salt is dissolved at room temperature in its own weight of distilled water, with the aid of a motor-driven stirrer. The solution must be filtered until perfectly clear; it may then be placed in a large crystallizing dish in a small room, free of dust; it is of advantage to remove the water vapor by appropriate drying agents. The slow ensuing crystallization should yield perfectly transparent crystals. After about two-thirds of the water has evaporated, the mother liquor is poured off and *only the clear crystals are taken;* those that are white are redissolved and added to the mother liquor. The whole is then filtered and left to crystallize again. *The selected clear crystals are rinsed with distilled water, drained, and left to dry.*

To make a solution of cadmium sulphate for setting up cells, the pure crystals are put into an Erlenmeyer flask and covered with two-thirds their weight of distilled water. A suitable stirrer (Schultz stirrer, Ber. d. d. Chem. Ges., 1896, 2883) is driven by a motor, for the purpose of causing the water to circulate over the crystals, for at least half a day, preferably in a bath at 25° cent., controlled by a thermostat. The supernatant liquid should be clear and should remain so indefinitely. It should be left standing over the crystals. and when it is used it should be saturated at a temperature as high as 25° cent. The saturation of the solution is of great importance in order that the cells may quickly reach electrical equilibrium.

3. Cadmium Amalgam.

To prepare a 12.5 per cent. cadmium amalgam, free from zinc, a large crystallizing dish is nearly filled with a saturated solution of cadmium sulphate slightly acidulated with sulphuric acid. In a small, low crystallizing dish is placed a weighed quantity of pure mercury, and the whole is immersed in the cadmium sulphate solution. The pure cadmium of commerce is melted down into a large button with a stick of cadmium attached for electrical connection; or, several of the cadmium rods, bound together, are placed in a vertical position with their lower ends in the solution and beneath them a small, low crystallizing dish. If the cadmium disk or button is used, it is placed in the second low crystallizing dish, which retains the finely divided dross or powder. The metallic cadmium is then made the anode and the mercury the cathode, connection with the latter being made by means of a platinum wire sealed, except at its end, in a glass tube. The fall of potential from the anode to the cathode should not exceed 0.3 volt. An ammeter should be used to keep account of the quantity of electricity flowing through the cell, until something more than the necessary weight of cadmium has been deposited on the mercury cathode. The small crystallizing dish, containing the cadmium amalgam and some of the solution, is then removed and warmed over a bath till the amalgam melts under the cadmium sulphate solution. When cool it forms a crystalline disk. This method yields an amalgam free from zinc, and there is no oxide or dross formed, as there is when the amalgam is made by the method of heating. The solid amalgam should next be washed, dried on filter paper, and weighed. The necessary weight of mercury to make a 12.5 per cent. amalgam is finally added. The amalgam should be kept under a pure cadmium sulphate solution, and it

must be melted on a water bath to insure homogeneity before it is used in making a cell.

4. Mercurous Sulphate.

In a flat-bottomed glass vessel or deep crystallizing dish place pure redistilled mercury two centimetres or more deep. Cover with dilute sulphuric acid (one of acid to six of water) to a depth of 8 or 10 cm. Make electrical connection with the mercury as the *anode* by means of a platinum wire covered, except at its end, by a glass tube. For a cathode use a piece of sheet platinum so as to expose to the acid solution a surface of about 50 sq. cm. A current density of 0.5 ampere per 100 sq. cm. surface of mercury may be used. A crystalline mercurous sulphate forms soon after the current begins to flow from the mercury to the acid solution. A stirrer, consisting of a glass rod bent at right angles at the bottom, must be used to keep the mercury surface exposed. The foot of the stirrer must pass close to the mercury, and the stirrer must be driven rapidly by a motor to keep the mercury agitated.

A little over four grammes an hour can be prepared in this way with a current of half an ampere. The mercurous sulphate formed should be protected from the light, since mercurous sulphate darkened by exposure to light gives too high an electromotive force. The sulphate will be white or gray, according to the amount of finely divided mercury mixed with it. The presence of this mercury in a state of fine division is a distinct advantage. If the stirring is continued after the circuit is broken, the crystals of mercurous sulphate grow in size, become whiter, and subsequent treatment is easier.

The mercurous sulphate may be removed from the mercury by a separatory funnel. It should be kept under the acid solution, one to six, in contact with mercury and in the dark.

5. The Paste.

When ready to fill a cell, the mercurous sulphate, which has been kept in contact with mercury under dilute sulphuric acid, is brought into a Gooch crucible of about 25 c.c. capacity (about three-fourths), avoiding much free mercury, which interferes with the filtering. A tiny filter paper covers the perforations in the bottom of the crucible, and the whole is mounted on a Bunsen filter flask and attached to a filter pump.

The mercurous sulphate is first washed a couple of times with dilute sulphuric acid (15 c.c. concentrated acid to a litre of water), and then with the saturated cadmium sulphate solution. The washing with the cadmium sulphate solution should be repeated five or six times to remove all the acid; only a few c.c. of the solution are needed for a single washing; after each washing the cadmium sulphate solution is to be removed as completely as possible by the filter pump. The last washing leaves the salt ready to be made into a paste. The top layer after the last washing should be verified.

The paste is then made in a clean agate mortar by grinding together crystals of the pure cadmium sulphate and a little mercury, and then mixing in about three volumes of the mercurous sulphate; finally add enough saturated cadmium sulphate solution to make a thin paste.

6. Construction of the Cell.

The *H*-form of cell is the most convenient to fill. Fig. 2 shows the glass cell half actual size, ready to be filled. The tubing is drawn out

and contracted at *a* so as to leave the diameter about 6 cm. and with thin walls at this point. The amalgam is melted over a water bath and is introduced by means of a small tube, slightly contracted at the end, and of a diameter that will allow it to pass freely through the neck *a*. The warmed tube is used as a pipette, and permits the rapid introduction of the amalgam without splashing. It should always be wiped with a filter paper or clean cloth before it is introduced into the cell.

The mercury, the thin paste, and the concentrated cadmium sulphate solution may be introduced in the same manner. An alternative method is to fill the cell through little funnels, made out of small test tubes. They must pass through the neck at *a*, and reach well down toward the bottom. After the mercury and the paste have been introduced, both legs of the cell are filled with clean, dry crystals of cadmium sulphate. Enough of the saturated cadmium sulphate solution is finally added to fill the cell to the top of the cross connecting tube.

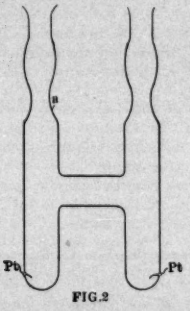


FIG. 2

The sealing off is readily done by means of two small horizontal blast flames, 5 cm. long, directed in a line toward each other and just meeting. The narrow part at *a* is brought between the impinging flames, the glass quickly softens, and the top part is drawn off. A cell sealed in this way contains nothing but the necessary materials of the voltaic combination. It can not leak, and can be immersed in a kerosene bath without danger that the oil will penetrate into the inside, as it does with sealing wax and paraffin.

After soldering copper wires to the platinum terminals of the cell, it is desirable to tie them securely with thread to the legs of the cell, as a precaution to avoid the breaking off of the platinum wire at the point where it enters the glass.

The Committee is indebted to Dr. Hulett for many suggestions in the preparation of these Specifications.

HENRY S. CARHART, Chairman,
EDWARD B. ROSA,
CLAYTON H. SHARP,
GEORGE A. HAMILTON,
} Committee.

REPORT OF LIBRARY COMMITTEE.

We beg to submit herewith a report of the present state of the Library of the INSTITUTE, and the state of the several funds under the cognizance of this Committee.

During the past year no accessions by gift to the funds of the Library have been received, and a much smaller number of books have been added to the Library through donations than in the previous two years. This does not, however, signify any decrease of interest in the Library on the part of members, but follows from the fact that in view of the great sum of money to be raised by the INSTITUTE to fulfil the obligations assumed in connection with the Union Engineering Building, your Committee has refrained during the year from pressing upon the membership the claims of the Library to their support.

During the past year about $1000 was expended in the purchase of books in the English, German and French languages, the several lists prepared for this purpose having been carefully compiled to include the titles of the more authoritative works published during the past twenty years. The preparation of further lists of modern books required to meet ordinary needs has been deferred until some definite conclusions shall have been arrived at concerning the scope and organization of the proposed library for which quarters are to be provided in the Union Engineering Building, and of which the INSTITUTE collection will probably form part.

A catalogue of the periodical publications in the Library, including the Transactions of professional and scientific bodies, has been prepared and is now in press. In this the entries of

the periodicals which the Library does not possess in complete state will be followed by a note pointing out the portions lacking; and as a copy of the catalogue will be sent to each member of the INSTITUTE, it is hoped that this indication will lead to members giving their aid in filling out incomplete sets.

The Library has received from the C. & C. Electric Company, the Crocker-Wheeler Company, the General Electric Company, the Stanley Electric Mfg. Company, and the Westinghouse Electric & Mfg. Company, sets as complete as could be made at the present day, of the trade and engineering publications issued by these several companies. It is hoped that similar collections may be obtained from other electrical manufacturing companies; literature of this class will be valuable for future historical purposes, and the Library of the INSTITUTE would appear to furnish an excellent means for its preservation.

Sets as complete as could be provided have been obtained of the publications of the Underwriters' Electrical Association, the National Board of Fire Underwriters, the International Association of Municipal Electricians, the Massachusetts Board of Gas & Electric Light Commissioners, the League of American Municipalities and of the Municipal Electrical Departments of Philadelphia, Chicago, Detroit and South Norwalk, Conn. In the letter to be sent out with the catalogue of periodicals an appeal will be made to the membership to assist in building up the collection of this class of literature.

The compilation of the Wheeler Bibliography is now approaching completion and the MS. will probably be ready to place with the printer the latter part of the present year.

During the year gifts of books were received from the following:

ARNOLD, BION J.
BOWLER, F. T.
BRILLOUIN, M.
CHEMICAL PUBLISHING COMPANY
CALDWELL, EDWARD.
DODGE, F. M.
EDISON, THOMAS A.
ELLICOTT, E. B.
GODDARD, C. M.
GAUTHIER-VILLARS.
HANCHETT, GEORGE T.
HAMMER, W. J.
HOPPING, G. W.
HUTCHINSON, R. W., JR.
LINDERS, O.
MCGRAW PUBLISHING COMPANY.
MACVICAR, J.
MASSACHUSETTS BOARD OF GAS & ELEC. LIGHT COMMISSIONERS.
MEAD, MORRIS W.
MARTIN, T. C.
MORISON, J.
MULLIN, E. H
ROEBER, E. F
SAGER, J. C.
SMITHSONIAN INSTITUTION.
SPANG, H. W.
SYNDICAT DES FORCES HYDRAULIQUES.
TISCHENDORFER, F.
UNDERWRITERS NATIONAL ELECTRICAL ASSOCIATION.
U. S. CENSUS OFFICE.
D. VAN NOSTRAND COMPANY.
VARLEY, S.
WEAVER, W. D.
WILEY, J. & SONS.
WINCHESTER, A. E.
WOLCOTT, TOWNSEND.

As stated in the report last year, the gift of Mr. B. J. Arnold comprises a complete set of "Annalen der Physik" from 1790 to date. Mr. Arnold also defrayed the cost of binding or rebinding a number of volumes of the set, which is now in excellent condition.

Mr. Thomas A. Edison donated a complete set to date of the "Nuovo Cimento." Part of the set came from the library of Mr. Edison, who purchased abroad the volumes necessary to complete the set, and defrayed the cost of binding all the volumes uniformly in half-morocco.

The donation of Mr. Edward Caldwell consists of a set of "Popular Science Monthly," complete to 1900, in new half-morocco binding.

Mr. Edward D. Adams has requested your committee to complete to date at his cost the several sets of Royal Society publications which he presented last year to the Library. Mr. Adams has also very generously offered to subscribe in the name of the Library for the annual issues of the "International Catalogue of Scientific Literature" covering the branches of math-

ematics, mechanics, physics and chemistry, and numbering in these branches about six volumes yearly—the term of a subscription being fixed by the publishing committee at five years. This valuable publication, which supercedes the Royal Society Catalogue, is compiled under the auspices of a principal learned body in each of the leading countries of the world, the Smithsonian Institution representing the United States.

Following are the statistics of the Library brought up to May 1, 1904:

STATISTICS OF LIBRARY.

Source.	Titles.	Volumes.	Pamphlets	Valuation.
Report of May 1, 1903	6377	8139		$16,870.78
PURCHASES:				
Carnegie Fund	14	128		283.17
Donation Fund	114	120		258.62
Mailloux Fund		9		29.20
Institute Appropriation	299	366	22	785.19
Miscellaneous Pamphlets			92	23.00
Periodicals Bound	59	92		184.00
GIFTS:				
B. J. Arnold	1	332		1,304.72
Edward Caldwell	1	57		70.00
Thomas A. Edison	1	47		200.00
Miscellaneous Gifts (33 donors)	58	130		128.00
Total, May 1, 1904	6924	9420	114	$20,136.68
Duplicates	187	424		671.02
	6737	8996	114	$19,465.66
Duplicate Periodical Titles	64			
	6673	8996	114	$19,465.66

Following is the total valuation of the Library including permanent library fixtures:

TOTAL VALUATION.

Books	$20,136.68
Book Stacks	1,470.25
Furniture, Catalogue Cases, etc	130.20
	$21,737.13

Following are tabulations giving the present state of the several funds of which the Library Committee has cognizance:

CARNEGIE FUND.

Dr.		Cr.	
Balance May 1, 1903....	$4,864.10	Books.....	$283.17
Interest to May 1, 1904..	135.70	Wheeler Bibliography....	284.25
		Unexpended.....	4,432.38
	$4,999.80		$4,999.80

MAILLOUX ENDOWMENT FUND. ($1,000.)

Dr.		Cr.	
Interest Accrued.....	$29.50	Subscriptions.....	$20.20
		Continuation of Sets.....	9.00
		Unexpended.....	.30
	$29.50		$29.50

DONATIONS.

Dr.		Cr.	
Balance May 1, 1903.....	$635.04	Purchase of Books.....	$265.37
		Unexpended.....	369.67
	$635.04		$635.04

The table below gives an account of funds appropriated by the INSTITUTE for library purposes:

INSTITUTE APPROPRIATIONS.

Dr.		Cr.	
Balance May 1, 1903....	$785.45	Books.....	$785.19
Appropriation for Maintenance.....	3,000.00	Rent.....	1,505.04
		Insurance.....	54.77
Special Appropriation for book stacks.....	370.00	Salary, Librarian.....	780.33
		Extra Assistance.....	50.00
		Binding.....	254.20
		Book Stacks.....	370.00
		Library Supplies.....	65.36
		Subscriptions.....	20.00
		Miscellaneous.....	19.05
		Unexpended.....	251.51
	$4,155.45		$4,155.45

Annual Appropriation, 1904–1905.

The annual appropriation asked of the Institute for Library purposes is limited to the sum required solely for the maintenance of the Library. It includes no provision for the purchase of books or Library fixtures, nor for any other than routine expenses and binding. The requirements for the fiscal year May 1, 1904, to May 1, 1905, will be as follows, the item for binding including provision for rebinding the Library set of Patent Specifications, which is complete to June 30, 1891, and numbers 97 volumes:

Rent	$1,505.04
Insurance	65.00
Salary, Librarian	780.00
Extra Assistance	50.00
Binding	450.00
Library Supplies	100.00
Subscriptions	25.00
Express, Postage, Miscellaneous	24.96
	$3,000.00

Following is an itemized statement of disbursements from the annual appropriation of last year:

Rent	$1,505.04
Insurance	54.77
Salary, Librarian	780.33
Extra Assistance	50.00
Binding, Periodicals and Books	254.20
Library Supplies	65.36
Subscriptions	20.00
Express, Postage, Miscellaneous	19.05
Unexpended	251.25
	$3,000.00

For the Library Committee,

W. D. Weaver, Chairman.